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OFF-DESIGN THEORETICAL PERFORMANCE OF THREE TURBOFAN ENGINES FOR LIGHT SUBSONIC AIRCRAFT

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SUMMARY

Preliminary cycle performance calculations were made for three geared-fan turbofan engines. The three engines presented in this study do not represent a systematic variation of the engine parameters and design features because they are the result of some preliminary exploratory studies. However, they do illustrate several methods for alleviating high turbine inlet temperature and compressor surge problems.

In this study, the bypass ratio of 2.5, fan pressure ratio of 1.3, overall compressor ratio of 6.0, and turbine inlet temperature of 1300° F (704° C) were set at the cruise design point of 25 000 feet (7600 meters) and Mach 0.65. The net thrust required was 400 pounds (181 kg) at design and a minimum of 1000 pounds (453 kg) at sea level static. A maximum turbine-inlet temperature of 1500° F (817° C) was allowed at sea level static.

As power and rotational speed were reduced at cruise, turbine-inlet temperature decreased, surge margin remained adequate, and specific fuel consumption increased. These trends are typical of any normal turbofan engine when power is reduced. Power reduction at cruise was accomplished with the inlet and nozzle areas held fixed at their design values.

Matching of the engine components at the sea level static condition resulted in some problems. With the inlet and nozzle areas held at their design values, the turbine-inlet temperatures often exceeded 1500° F (817° C) and both the outer and inner compressors tended to operate in or near the surge region at full rated speed. As compressor speed was reduced, the problems became worse. A solution to the problems was found in each case. The solution consisted of varying the inlet area, primary nozzle area, secondary nozzle area, or some combination of these.

INTRODUCTION

There is currently some interest in the feasibility of low-cost, jet-powered private aircraft. This report considers the off-design thermodynamic performance of the geared turbofan engine, one possible type of engine for this application.

The geared fan configuration has only one main shaft. This shaft connects the inner compressor to the turbine. In addition, there is a reduction gear between the inner and outer compressor (fan) which allows the outer compressor to be driven at one-half the inner compressor speed. This assures low tip speeds for the outer compressor, which, in turn, helps keep noise to a minimum.

The purpose of this study was to estimate the off-design performance of three geared turbofan engines at sea level static and cruise conditions. Several methods for alleviating high turbine-inlet temperatures and compressor surge problems were evaluated. These methods included the use of variable-area exhaust nozzles, compromising cruise performance by providing the compressor design point with a large surge margin, and the use of inlet blockage to reduce the bypass ratio and outer compressor work.

At the conditions selected for cruise, Mach 0.65 and 25 000 feet (7600 m), good specific fuel consumption was obtained with a turbine-inlet temperature of 1300° F (704° C), a bypass ratio of 2.5, a fan pressure ratio of 1.3, and an overall compressor pressure ratio of 6.0. In the present study, these values were held fixed regardless of the engine design considered. Also held fixed was the design thrust level of 400 pounds (181 kg), a typical value for light jet aircraft at this Mach number and altitude.

At sea level static conditions, where a takeoff thrust of 1000 pounds (453 kg) is considered minimum for this type aircraft, it was assumed that the turbine-inlet temperature would be allowed to increase to 1500° F (817° C), if necessary in order to obtain this thrust level.

METHOD OF ANALYSIS

A limited performance study was made for three turbofan engines. The calculations were done by hand with the aid of the engine performance charts of reference 1.

Table I summarizes all the design point parameters. Several parameters were held constant at their design value regardless of off-design operating conditions. These were the combustor pressure loss of 6 percent and combustor efficiency of 0.98, and the primary and secondary nozzle pressure loss of 2 percent (unless otherwise noted). Inlet pressure recovery was held constant at 1.0 only at cruise altitude and speed.

All the other engine parameters varied. Inlet pressure recovery at sea level static varied as shown in figure 1. This schedule is an estimate based on reference 2 and an assumed inlet pressure recovery of 0.95 at 100 percent of design corrected airflow. Compressor off-design efficiencies, pressure ratios, and turbine-inlet temperatures were determined from the matching procedures of reference 3 using representative compressor maps. Bypass ratio was determined from the ratio of secondary to primary airflow. Because of the low turbine pressure ratios encountered in this study and the two-stage turbine, the usual simplifying assumptions of choked turbine flow could not be made. Instead, the schedule shown in figure 2 was used. This schedule was taken from reference 3. Also, a typical schedule of turbine efficiency versus velocity ratio was assumed. This schedule is shown in figure 3.

The required net thrust at cruise was 400 pounds (181 kg). At sea level static, a minimum of 1000 pounds (453 kg) thrust was required. If necessary, the turbine-inlet temperature was allowed to increase to a maximum of 1500° F (818° C) in order to achieve the 1000 pounds (453 kg) thrust at takeoff. These thrust levels are typical for a light plane.

Engine Description

The three engines examined were all geared turbofans, but they differed in design as schematically illustrated in figure 4.

In engines A and B, figure 4(a), there is a splitter from the inlet lip to the inner compressor face. This splitter physically divides the airflow at the inlet lip. Therefore, the bypass ratio is fixed as soon as the air enters the two separate sections of the inlet. Another feature of these two engines is the design of the primary portion of the outer compressor. This compressor is designed not to give a pressure rise to the primary airflow as it passes through. This allows the inner compressor face to have the same conditions as the outer compressor face. This assumption was for computational convenience. These two engines use a reduction gear to drive the outer compressor at one-half the speed of the inner compressor. The two-stage turbine is on a common shaft with the inner compressor. These engines have variable primary and secondary nozzle capabilities.

Engine C shares the same gearing concept along with the two-stage turbine and variable nozzle capabilities. But the splitter has been shortened to a more conventional length. This allows the airflow split and bypass ratio to be determined at station 2 instead of at the inlet lip as in engines A and B. So, computational convenience was sacrificed in engine C in order to achieve more accuracy. Also, engine C had a flap in the inlet, which was designed to control the airflow entering the engine. It was assumed that reducing the airflow by some percentage would reduce the outer compressor work by the same percentage.

Compressor Map Description

Besides the physical differences of the engines, they all used different compressor maps. All the compressor maps are shown in figure 5. The conventional compressor maps were derived from the generalized maps.

The generalized outer compressor map of engine A is shown in figure 5(a). The design point, the circled symbol, was chosen because of its high efficiency and moderate surge margin. The map of figure 5(a) was also used for engine B. The square symboled design point of engine B was chosen for extra surge margin at cruise. This forced the outer compressor of engine B to operate in a low efficiency region. Figure 5(b) shows the generalized outer compressor map of engine C. A different design approach for this compressor yielded corrected speed lines that are more rounded and not as steep as those of figure 5(a). The design point of engine C, the triangle symbol, was chosen for high efficiency and moderate surge margins.

The generalized inner compressor map used for engines A, B, and C is shown in figure 5(c). The circled point corresponds to the design point for engine A, squared point is the design point of engine B, and the triangle point is the design point for engine C. These points were chosen for the same reasons mentioned for choosing the design points on the outer compressors of each engine. Table II summarizes some of the aspects of design point location and compressor map type.

For reference, the actual compressor maps of all the engines are presented in figures 5(d) through 5(i). Figures 5(d), 5(e), and 5(f) are the outer compressor maps of engines A, B, and C, respectively. Figures 5(g), 5(h), and 5(i) are the inner compressor maps of engines A, B, and C, respectively.

RESULTS AND DISCUSSION

Generalized compressor maps were used to calculate performance throughout this study. The resulting equilibrium operating lines are shown only on the generalized compressor maps.

Performance of Engine A

The two generalized compressor maps used for engine A during cruise are shown in figure 6. These maps are the same as the maps in figures 5(a) and 5(c). The surge margin is adequate for both compressors during part power operation, figures 6(a) and 6(b). All the calculations at cruise assumed fixed values of nozzle exit areas.

Figure 7 shows turbine-inlet temperature and net thrust versus compressor speed at cruise conditions. Turbine-inlet temperature decreases smoothly from its design value and so does net thrust as compressor speed is reduced. At around 75 percent of design compressor speed, the net thrust is zero.

Specific fuel consumption for engine A is 0.95 hr^{-1} at the design net thrust of 400 pounds (181 kg). This is shown in figure 8. As power is reduced, specific fuel consumption increases in a normal manner.

During sea level static operation, some problems were uncovered. The problems related to lack of surge margin and high equilibrium turbine-inlet temperatures. To overcome these problems, it was necessary to vary nozzle exit areas at certain times. To evaluate the most optimistic case, inlet pressure recovery was assumed to be 1.0 and nozzle pressure loss was assumed to be zero at certain times. All of these assumptions are noted on the appropriate figures.

One of the goals of the sea level static calculations was to achieve 1000 pounds (453 kg) net thrust without exceeding a turbine-inlet temperature of 1500° F (817° C) at design compressor speed. Another goal was to be able to operate the engine at idle with sufficient surge margin and turbine-inlet temperature no higher than 1500° F (817° C). Idle speed was assumed to be that speed at which net thrust was 6 percent of the minimum allowable takeoff thrust; i.e., 60 pounds (27 kg).

It was assumed that the engine starter would take the engine to about 30 percent of design compressor speed. From this point, the engine had to accelerate to idle speed. This meant that the engine needed some surge margin at 30 percent of design compressor speed in order to accelerate. This was another sea level static goal of this study.

The generalized compressor maps of engine A are shown again in figures 9(a) and 9(b). The points and lines corresponding to various values of secondary nozzle exhaust area (A_{6_s}) are shown in figure 9(a), the outer compressor map. Opening A_{6_s} allows the outer compressor to move away from surge. Also shown in this figure is the effect that improving inlet pressure recovery and secondary nozzle pressure loss has on surge margin. This is shown at A_{6_s} = 160 percent (the open symbols compared with the solid symbols). For this compressor at sea level static, 95 percent of reference corrected speed corresponds to 100 percent of design rotational speed.

The inner compressor map is shown in figure 9(b). The effects of varying primary exhaust-exit area (A_{6_p}) and A_{6_s} are shown in this figure. Again, 95 percent of design corrected speed corresponds to 100 percent of design compressor speed. This is because the face of the inner compressor has sea level static conditions since the outer compressor is assumed to do no work on the primary flow.

With A_{6_p} and A_{6_s} at their design values, both compressors operate in surge as shown in figure 9. In order to avoid surge at design speed, the outer compressor needs an A_{6_s} = 106 percent. The inner compressor needs at least an A_{6_s} = 116 percent if A_{6_p} is held at 100 percent and surge is to be avoided. Actually, in order to reach compressor speeds of about 30 percent of design without hitting surge, this engine would have to have an A_{6_p} = 165 percent and A_{6_s} = 264 percent, figure 9(b). This is with the inlet pressure recovery of 1.0 (as shown in fig. 1 at these low airflows) and secondary nozzle pressure ratio of 1.0. So, this engine can reach 30 percent compressor speed with some surge margin if inlet pressure recovery is very good and the nozzle pressure losses are kept to a minimum.

Figures 10(a) and 10(b) show the effect of compressor speed and various values of A_{6_p} and A_{6_s} on turbine-inlet temperature and net thrust. With A_{6_p} = 100 percent, A_{6_s} has to be at least 130 percent to stay within the 1500° F (817° C) turbine-inlet temperature limit (fig. 10(a)). This figure shows the tendency for temperature to increase as speed is reduced. The combination of A_{6_p} = 165 percent and A_{6_s} = 264 percent looks good from the standpoint of temperature as well as surge. At 30 percent compressor speed, the turbine inlet temperature should be about 1200° F (650° C).

Minimum takeoff thrust can be obtained at 100 percent speed with A_{6_p} = 100 percent and A_{6_s} = 130 or 160 percent (fig. 10(b)). Idle speed would be at 60 percent compressor speed where the temperature is 1130° F (612° C) and the thrust is 60 pounds (27 kg). This allows surge margin on both compressors for acceleration (figs. 9(a) and 9(b)).

Engine A will meet the requirements of this study if the cost of variable nozzles is not too great, but it will have skimpy surge margins at low compressor speeds. By picking the design point farther from surge to begin with, it was hoped that engine B would solve this problem.

Performance of Engine B

The design points for engine B are shown in figure 11, repeated from figure 5. The reason for selecting such a low point for design is because engine A exhibited a lack of surge margin at sea level static conditions. The large surge margins forced both compressors of engine B to operate at lower levels of efficiency than engine A.

At cruise, only design point calculations were made for engine B. For the design turbine-inlet temperature and design net thrust, the specific fuel consumption of engine B is 1.13 hr^{-1}. Trends in surge margin, turbine-inlet temperature, net thrust, and specific fuel consumption for engine B are expected to be similar to those of engine A as power is reduced during cruise.

Sea level static compressor operation is shown on the generalized compressor maps of engine B, figures 11(a) and 11(b). The points and lines corresponding to various values of A_{6_s} are shown in figure 11(a), the outer compressor map. For this compressor, 95 percent corrected speed corresponds to 100 percent of design speed.

Maintaining A_{6_s} at 100 percent does not force the outer compressor of engine B into surge as with engine A. So, lowering the design point did help the surge problem. But, as mentioned before, the design point selected for engine B forces the outer compressor to operate in a low compressor efficiency region.

Opening A_{6_s} to 244 percent appears to allow ample surge margin for the outer compressor at speeds of 30 percent, figure 11(a).

With A_{6_s} of 244 percent, and an A_{6_p} of 100 percent, ample surge margin exists at low and high inner compressor speeds as shown on the generalized inner compressor map of engine B, figure 11(b). The small surge margin problem of engine A has been eliminated in engine B. However, the turbine-inlet temperature problem has been enlarged in engine B as compared to engine A. The extent of this problem is examined in the next figure.

Figures 12(a) and 12(b) show the effects of compressor speed and various values of A_{6_s} and A_{6_p} on turbine-inlet temperature and net thrust. It also shows the effect of operating in the parts of a compressor map where the efficiency is poor. Opening A_{6_s} from 100 to 244 percent only lowers the turbine-inlet temperature about 120° F (67° C) at 100 percent compressor speed (fig. 12(a)). This is because the work of the outer compressor is not falling off very fast as A_{6_s} is opened. This is due to rapid deterioration of already poor efficiency. By comparison, as A_{6_s} is opened from 100 to just 160 percent in engine A, the temperature falls off 500° F (278° C), figure 10(a).

Opening A_{6_p} to 100 percent and A_{6_s} to 244 percent does allow engine B to develop the minimum takeoff thrust with the maximum allowable temperature at 100 percent compressor speed (fig. 12). So, this engine is acceptable from this standpoint. Idle speed turned out to be 56 percent compressor speed. The thrust is 100 pounds (45 kg), a little more than the desired 60 pounds (27 kg). This is a result of not wanting to go to lower compressor speeds because turbine-inlet temperature would exceed 1500° F(817° C). This 1500° F (817° C) temperature is 370° F (206° C) higher than the temperature of engine A at idle speed. This is a result of the lower compressor efficiencies and slightly higher compressor pressure ratio encountered at low speed by engine B as compared to engine A. Both compressors of engine B have ample surge margin at idle as shown in figures 11(a) and 11(b).

Engine B does meet the requirements necessary but has some high turbine-inlet temperature problems that are marginally acceptable. But engine B does exhibit larger surge margins than engine A. From that standpoint, it is better than engine A. From the turbine-inlet temperature and cruise efficiency points of view, it is worse. It is possible that the design point of engine B was too far from surge. An engine with a design point somewhere between that of engine A and engine B might be better. It would show more surge margin than engine A and probably less temperature problems than engine B.

A fan engine exhibiting a uniform pressure rise across the entire span of the outer compressor blades was examined next. Thus, computational convenience was sacrificed for more accuracy. Also, a new generalized outer compressor map was used in order to evaluate the effect of differently shaped speed lines.

Performance of Engine C

The design points for engine C are shown in figure 13 as well as figures 5(b) and 5(c). The high levels of efficiency achieved by the compressors of engine C along with the moderate surge margins, are similar to those of engine A. But the speed lines of the outer compressor of engine A tended to drop off more sharply than those of engine C. The shape of the speed lines had no noticeable effect on engine C during cruise since only design point calculations were made.

Performance without inlet blockage.- For the design temperature and thrust, the specific fuel consumption of engine C is 0.961 hr^{-1} at cruise conditions. Trends in the surge margin, turbine-inlet temperature, net thrust, and specific fuel consumption of engine C are expected to be similar to those of engine A as power is reduced during cruise.

Sea level static compressor operation is shown on the generalized compressor maps of engine C, figure 13. The generalized outer compressor map, figure 13(a), is different from the generalized outer compressor map of engines A and B. These differences have been mentioned before. But as a result of these differences, opening A_{6_S} along a constant speed lines does not decrease the outer compressor work in the map of figure 13(a) as it did for engines A and B using the map of figure 9(a). The reason that work does not decrease is that the speed lines are not steep enough. So, the work contributed by pressure ratio is not falling off as fast as the work contributed by the airflow is increasing. Therefore, opening A_{6_s} will not help reduce turbine-inlet temperature for engine C as it did with engines A and B. This compounds the high temperature problems and indicates that as steep a speed-line slope as other engine considerations may allow should be designed into the fan of these engines.

Shown in figure 13(a) are several points and lines corresponding to various values of A_{6_s}. Since the outer compressor has sea level static air at its face, 95 percent corrected speed is the same as 100 percent compressor speed for engine C. (The line labeled A_{6_s} = 0 percent will be discussed later.)

The inner compressor map of engine C is shown in figure 13(b). Points and lines of constant A_{6_p} and A_{6_s} values are shown. Inner compressor corrected speed lines do not correspond to outer compressor corrected speed lines in this engine. This is because the outer compressor causes some change in total temperature to the primary air passing through it. So, the air at station 2p in figure 4(b) is not at sea level static conditions.

Starting at about 96 percent corrected speed at the point labeled A_{6_p} = 100 percent and A_{6_s} = 106 percent, holding A_{6_p} fixed and opening A_{6_s} to 235 percent forces the compressor toward surge (fig. 13(b)). This is the reverse effect that opening A_{6_s} had on engines A and B, figure 9(b), for example. So, for engine C, A_{6_s} should be kept as near 100 percent as safe outer compressor surge margin will allow.

Opening A_{6_p} with a fixed value of A_{6_s} has the usual effect of moving the operating point away from surge. It appears from figure 13(b) that inner compressor speeds of around 70 percent can be obtained before surge is intersected. This could be done with A_{6_p} = 180 percent and A_{6_s} = 131 percent. Opening A_{6_p} any farther yields very little increase in surge margin at this point, and opening A_{6_s} would push the inner compressor into surge. If A_{6_s} could be closed some, this would help the inner compressor. But closing A_{6_s} is impossible since, at about 70 percent speed, a value of A_{6_s} less than 131 percent puts the outer compressur in surge (fig. 13(a)). To get to lower compressor speed, another variable is necessary. But before examining this other variable, the performance of engine C from 100 percent to 70 percent compressor speed is shown in the next two figures.

Performance for engine C at 100 percent compressor speed is shown in figure 14. In this figure, net thrust is plotted versus turbine-inlet temperature for lines of constant A_{6_p} and A_{6_s}. Two bounds are shown. One is the temperature limit and the other is the minimum sea level static thrust required in this study. Only the small upper left portion of the curve remains within the bounds. There are several acceptable combinations of A_{6_p} and A_{6_s} that will yield 1000 pounds

(453 kg) net thrust at temperatures equal to or less than 1500° F (817° C). One such combination, which was discussed in the previous figure, is an A_{6_p} = 140 percent and A_{6_s} = 131 percent. Another point that is acceptable on figure 14 is A_{6_p} = 100 percent and A_{6_s} = 106 percent. But with A_{6_s} = 106 percent, the outer compressor is operating on the surge line (fig. 13(a)).

The conclusion is that engine C will meet the takeoff requirements of this study.

Turbine-inlet temperature and net thrust for engine C are shown in figure 15 versus compressor speed. The performance is examined only to about 70 percent speed because of the surge problems shown in figure 13. Actually, both compressors go into surge at about the same speed. The trend for turbine-inlet temperature to increase rapidly as compressor speed is reduced is shown in figure 15(a). This trend is so sharp that none of the otherwise acceptable combinations of A_{6_p} and A_{6_s} can be used below about 80 percent compressor speed. At speeds below 80 percent, the temperature limit is exceeded.

The minimum thrust at 80 percent speed is about 500 pounds (227 kg) according to figure 15(b). This amount of thrust is too much for idle. So, engine C cannot idle with just variable A_{6_p} and A_{6_s} without forcing one or both compressors into surge and at the same time exceeding the temperature limit.

<u>Performance with inlet blockage</u>.- The solution to these low compressor speed problems may be to block part of the inlet flow and at the same time close A_{6_s}. This means all the air entering the inlet will have to go through only part of the outer compressor and then directly to the inner compressor. The engine then has a bypass ratio of zero and it becomes a turbojet. This inlet blockage could be completely variable or just have one or more preset position. In either case, it is obvious that the airflow of the inner and outer compressors must be identical and the following equation must hold.

$$\mathrm{CORW2p} = \mathrm{CORW1}\,\frac{(100\%\text{-Blockage})}{100\%}\left[\frac{P_1}{P_2}\right]\left[\frac{T_2}{T_1}\right]^{1/2}$$

where:

CORW2p = corrected airflow of the primary stream at station 2.

CORW1 = corrected airflow of the entire stream at station 1.

P = total pressure   1 = station 1

T = total temperature   2 = station 2

Using this equation and selecting various percentages of blockage, figure 16 was constructed for the compressors of engine C at 74 percent of compressor design speed. This equation assumes that blocking a certain percent of the inlet area will also block the same percent of the normal outer compressor airflow.

Turbine-inlet temperature is plotted versus percent of design inlet blockage for lines of constant A_{6_p} in figure 16. Surge limits of both compressors are noted on the figure. A blockage of 87 percent with A_{6_p} = 100 percent yields a temperature of about 750° F (399° C). The same blockage with A_{6_p} = 180 percent lowers the temperature to about 700° F (372° C). Both points are away from the surge limits shown. A check of figures 13(a) and 13(b) at about 70 percent corrected speed will confirm this. At this speed, ample surge margin is available for the lines labeled A_{6_s} = 0 percent (fig. 13(a)) and A_{6_p} = 100 percent and 180 percent with A_{6_s} = 0 percent (fig. 13(b)).

At 40 percent corrected speed, a point was selected on the outer compressor that would yield a satisfactory point on the inner compressor with 87 percent blockage. These points are shown in figures 13(a) and 13(b). If the point on the outer compressor had been selected closer to surge, the inner compressor would have gone into surge. If the point on the outer compressor had been selected further from surge, a higher inner compressor corrected airflow would have been required. This would have quickly forced the inner compressor down the corrected speed line to a point where the primary nozzle pressure ratio approached 1.0.

Some similar considerations determined the point near 80 percent corrected speed in figures 13(a) and 13(b). The outer compressor is operating in a stable region at this speed with A_{6_s} = 0 percent. But with A_{6_p} = 100 or 180 percent and A_{6_s} = 0 percent, the inner compressor goes into surge. If the blockage were reduced at this speed, a more favorable inner spool operation could be achieved. But with blockage fixed at 87 percent, inner compressor surge does limit the compressor speed range to between 40 and 80 percent. This is just enough range to complete the curves started in figure 15.

Figures 17(a) and 17(b) are a repeat of figures 15(a) and 15(b) from 80 to 100 percent compressor speed. Below 80 percent speed, the performance shown is for engine C with the inlet blocked 87 percent and the secondary nozzle area shut (A_{6_s} = 0 percent).

Turbine-inlet temperature varies from about 1180° F (581° C) at 40 percent speed to about 700° F (372° C) at 80 percent speed for A_{6_p} = 100 percent and A_{6_s} = 0 percent (fig. 17(a)). Over the same speed range, thrust increases from almost 0 pounds (0 kg) to about 100 pounds (45 kg) for the same A_{6_p} and A_{6_s}. Idle is 69 percent compressor speed. The corresponding temperature is 800° F (428° C). The idle speed allows good surge margins and temperature margins for acceleration.

Somewhat greater blockage would allow operation down to the desired 30 percent speed. Less blockage would allow operation at speeds above 80 percent. But 87 percent blockage is sufficient to show that the engine can have surge and temperature margins for acceleration from low speed to 80 percent speed. At about 80 percent speed, the blockage can be removed as A_{6_s} is opened to 131 percent. If A_{6_p} is opened to 140 percent at this time, the engine will be operating along the line labeled A_{6_p} = 140 percent and A_{6_s} = 131 percent in figures 17(a) and 17(b). Continued acceleration will cause the engine to reach design speed where it will develop the required takeoff thrust at a temperature of 1300° F (704° C).

Actually, to satisfy all the constraints of engine acceleration, the blockage should be varied from about 94 percent at 30 percent speed to 70 percent at 100 percent speed. This type of operation would yield low turbine-inlet temperatures and good surge margins over the entire compressor speed range. At some speed around 90 percent of design, the blockage could be removed and normal engine operation could be continued.

Other than making it more convenient to do the calculation, switching from engine configuration A (fig. 4(a)) to engine configuration C (fig. 4(b)) had little effect on performance. Most of the problems of engine C are a result of the outer compressor speed lines being rounded.

Moreover, inlet blockage need not be restricted to engine C. Engines A and B would have showed lower turbine inlet temperatures if their inlet had used some blockage. The best combination might have been the configuration of engine C, with the outer compressor map of engine A and, possibly, using some inlet blockage if needed.

Inlet blockage, as considered in this study, was an idealized situation. The actual gains to be derived from partially blocking an inlet may not be as great as this study assumed. Experimental tests will be required to verify the predicted effects of inlet blockage.

CONCLUDING REMARKS

A limited study was performed that estimated the off-design performance of three geared turbofan engines. The engines were sized at the cruise conditions of Mach 0.65 and 25 000 feet (7600 meters), which called for 400 pounds (181 kg) net thrust with a turbine-inlet temperature of 1300° F (704° C), a bypass ratio of 2.5, a fan pressure ratio of 1.3, and an overall compressor pressure ratio of 6.0. The minimum allowable takeoff thrust was 1000 pounds with a maximum turbine inlet temperature of 1500° F (817° C). The engines were required to exhibit stable equilibrium operation within the specified turbine temperature limits as compressor speed was reduced. At cruise, compressor speeds from 100 percent to 70 percent were examined. At sea level static, compressor speeds from 100 percent to 30 percent were examined.

All three engines examined in this study had some problem with high turbine-inlet temperature and/or lack of surge margin. These problems occurred at sea level static conditions and were more severe at low than at high rotational speeds. Cruise conditions presented no problems.

To solve the problems at sea level static condition, different compressor maps were tried as well as three degrees of variable geometry. These variable geometry components were primary and secondary nozzle exhaust area and inlet area.

Opening the secondary nozzle exhaust area always increased the outer compressor surge margin. Opening the secondary exhaust nozzle also reduced the work of the outer compressor as long as the speed lines of the outer compressor were steep enough. This reduction of compressor work reduced the turbine work and allowed lower turbine-inlet temperatures and greater surge margin for the inner compressor for any given primary nozzle area.

Opening the primary nozzle area always reduced the turbine-inlet temperature and increased the inner compressor surge margin. It was necessary to open both nozzles in order to achieve acceptable turbine-inlet temperatures and surge margins at low compressor speeds during sea level static operation.

Another method for reducing outer compressor work and therefore turbine-inlet temperatures was to reduce the flow of air to the outer compressor. This was done by partially blocking the inlet. It was found that, with the inlet blocked 87 percent and the secondary nozzle closed completely, one of the otherwise unacceptable engines operated within the specified limits between 40 and 80 percent compressor speeds. Above 80 percent speed, nozzle areas were varied with the inlet unrestricted to achieve the required takeoff performance.

To obtain more surge margin during sea level static operations, one engine compromised cruise performance by allowing a large surge margin at cruise. When the engine rotational speed was reduced at sea level static, more surge margin did result for this engine. But the compressor efficiencies were much lower than for the other engines. These low efficiencies resulted in turbine-inlet temperature problems for this engine.

It is concluded that:

1. The surge and turbine temperature problems of geared turbofan engines at sea level static conditions are less severe when the fan is designed so that its map has steep constant speed lines.

2. Lowering the design point to achieve more surge margin may be a good idea if the point is not lowered so far from surge that poor efficiency causes increased turbine-inlet temperature problems in off-design operation.

3. Partially restricting the inlet airflow will reduce the turbine-inlet temperature if it reduces the fan work.

4. Some degree of variability is needed in both primary and secondary exhaust nozzles in order to operate the engines from 30 percent to 100 percent compressor speed and stay within the restrictions of surge and turbine-inlet temperature.

5. Good inlet pressure recovery reduces the probability of encountering surge and high turbine-inlet temperatures.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 24, 1968,
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TABLE I.- Design Point Parameters

(Mach 0.65 and 25 000 Feet (7600 Meters))

Engine Parameter	Engine A	Engine B	Engine C
Inlet total pressure recovery, P_1/P_o	1.0	1.0	1.0
Outer compressor efficiency, η_{oc}	.85	.69	.85
Outer compressor pressure ratio, P_2/P_1	1.3	1.3	1.3
Inner compressor efficiency, η_{ic}	.83	.776	.83
Overall compressor pressure ratio, P_3/P_1	6.0	6.0	6.0
Bypass ratio, BPR, $\dot{W}_s/\dot{W}_p$	2.5	2.5	2.5
Combustor total pressure loss, $(1 - P_4/P_3)100$, percent	6	6	6
Combustor efficiency, η_{cb}	.98	.98	.98
Turbine inlet temperature, °F (°C)	1300 (704)	1300 (704)	1300 (704)
Turbine efficiency, η_t	.85	.85	.85
Primary nozzle total pressure loss, $[1-(P_6/P_2)_p]$ 100, percent	2	2	2
Secondary nozzle total pressure loss, $[1-(P_6/P_2)_s]$ 100, percent	2	2	2
Engine airflow, $\dot{W}_a$, lb/sec (kg/sec)	27.2 (12.8)	33.0 (14.95)	27.4 (12.86)
Net thrust, F_N, lbs. (kilograms)	400 (181)	400 (181)	400 (181)
Specific fuel consumption, SFC, hr^{-1}	.95	1.13	.961

TABLE II.- Compressor Design Points for Engines A, B, and C

Engine	Outer Compressor				Inner Compressor			Overall Compressor
	PR (1)	η (2)	Surge Margin	Remarks	PR (1)	η (2)	Surge Margin	PR (1)
A	1.3	.85	Moderate	Steep speed lines	6.0	.83	Moderate	6.0
B	1.3	.69	Large	Steep speed lines	6.0	.776	Large	6.0
C	1.3	.85	Moderate	Rounded speed lines	4.61	.83	Moderate	6.0

(1) - pressure ratio

(2) - efficiency

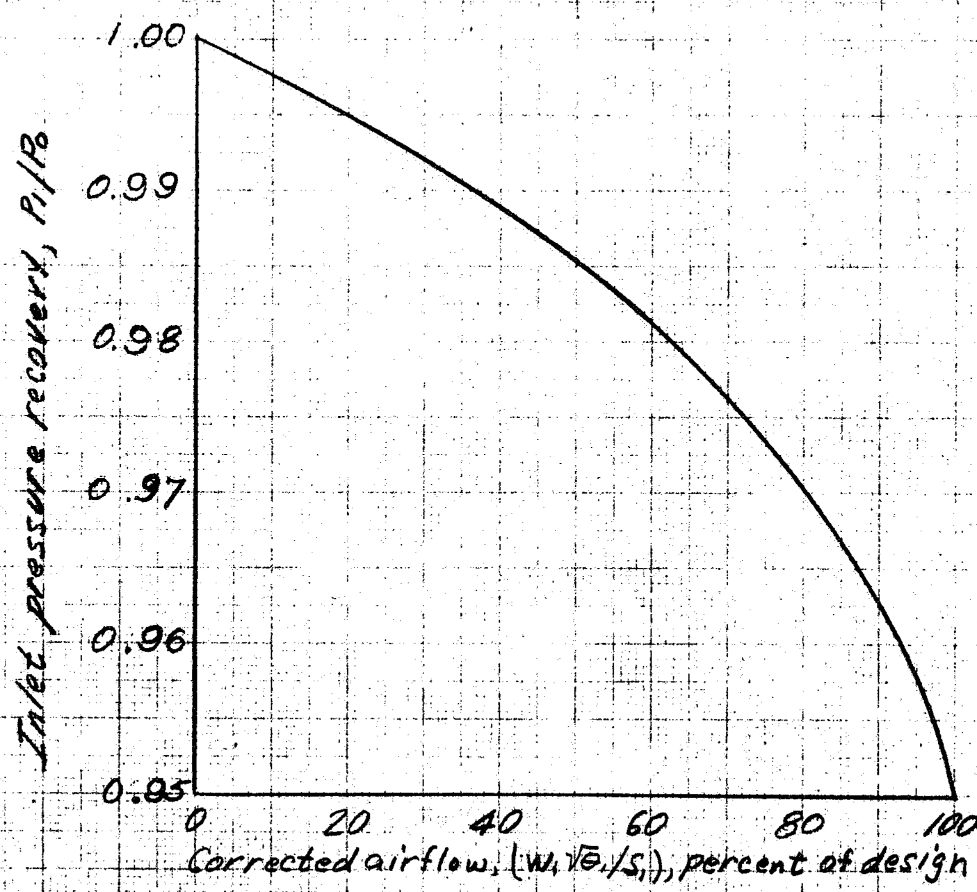


Figure 1. - Effect of outer compressor corrected airflow on inlet pressure recovery at sea-level-static conditions.

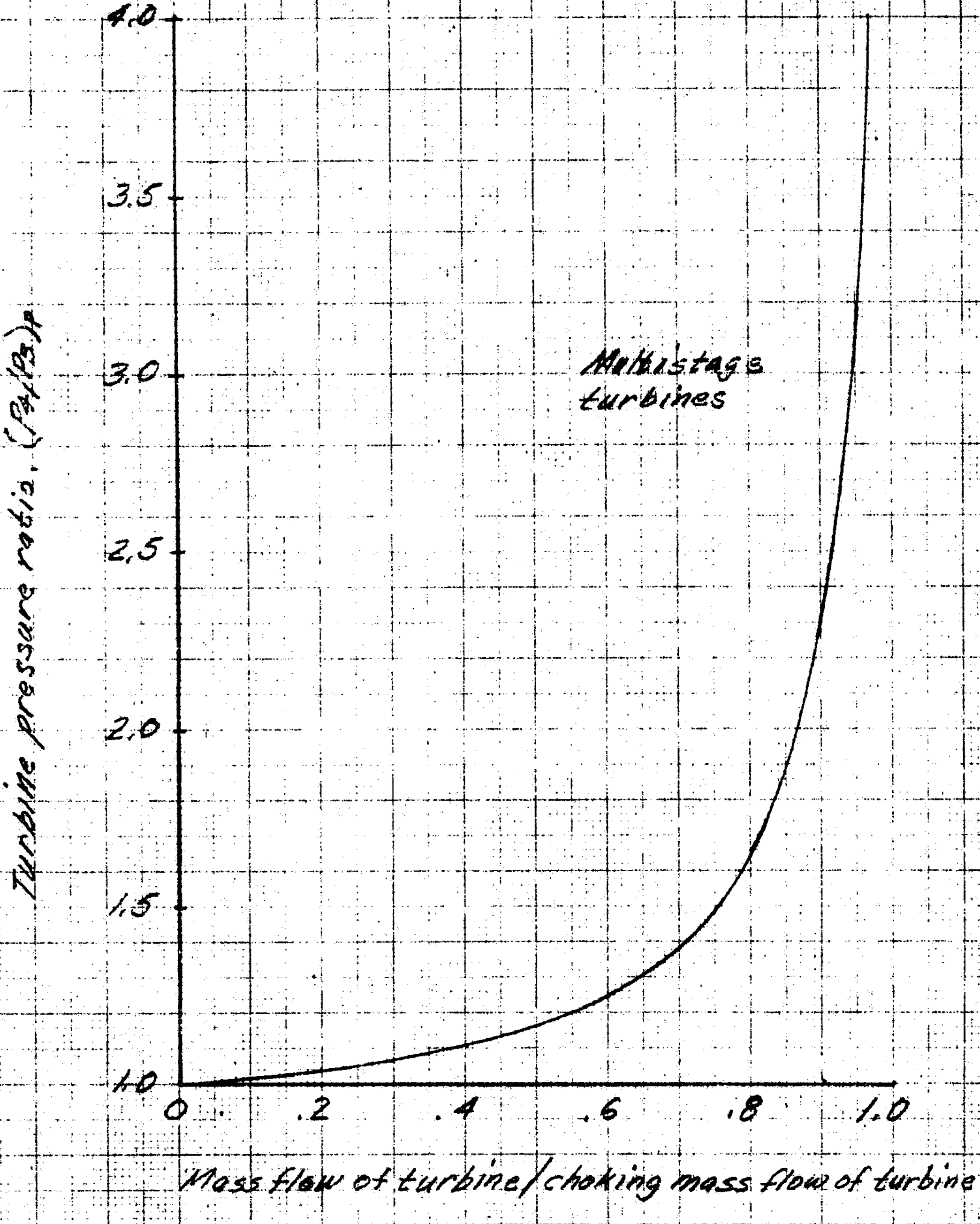


Figure 2.- Effect of turbine pressure ratio on turbine mass flow ratio.

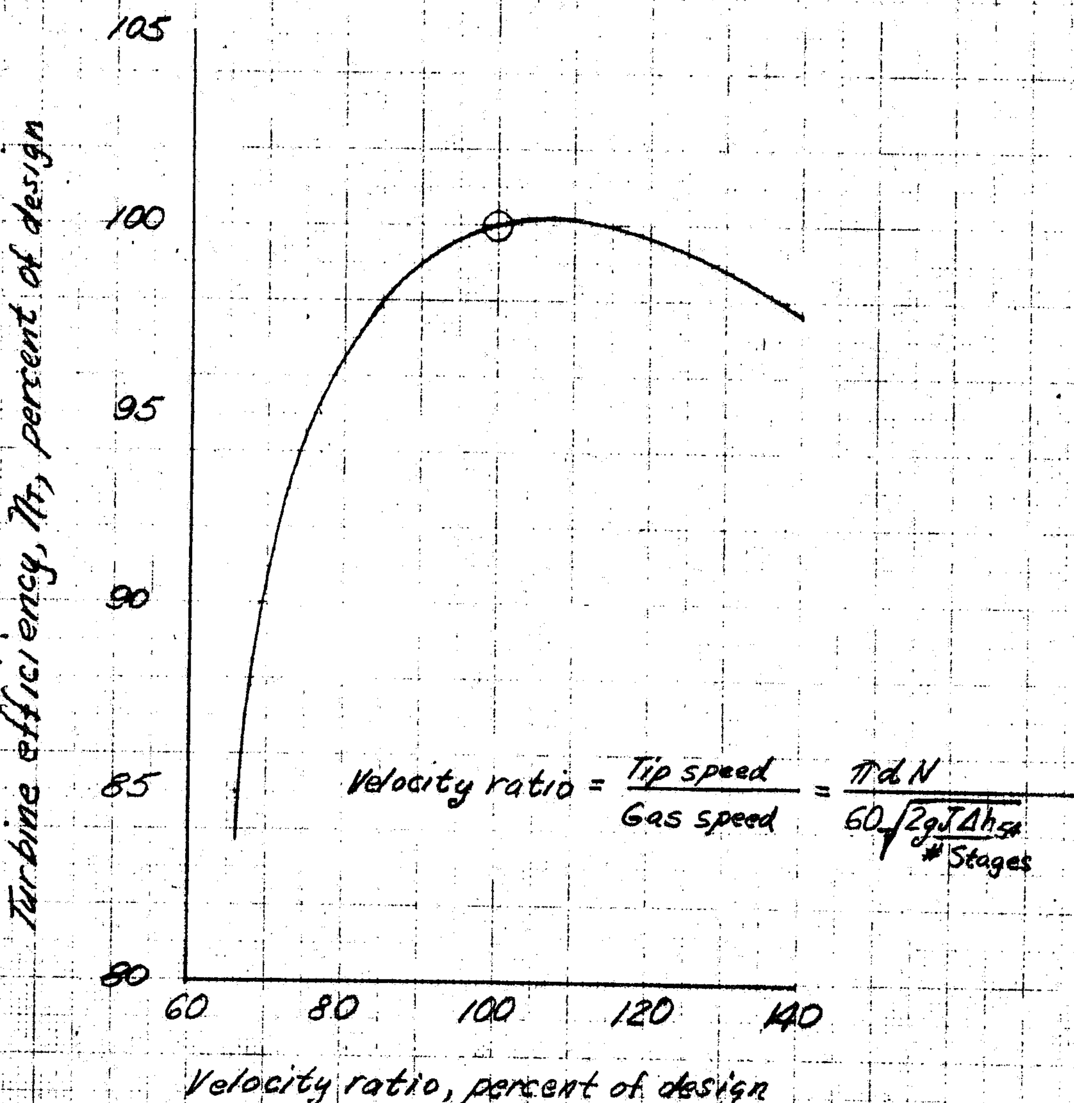
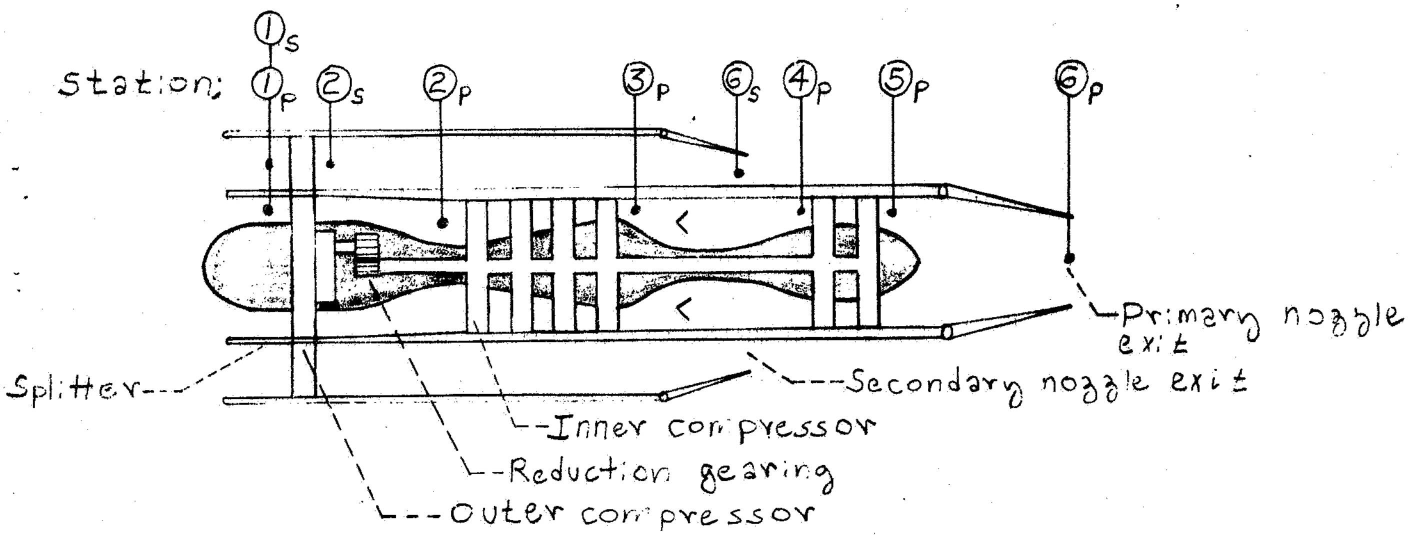
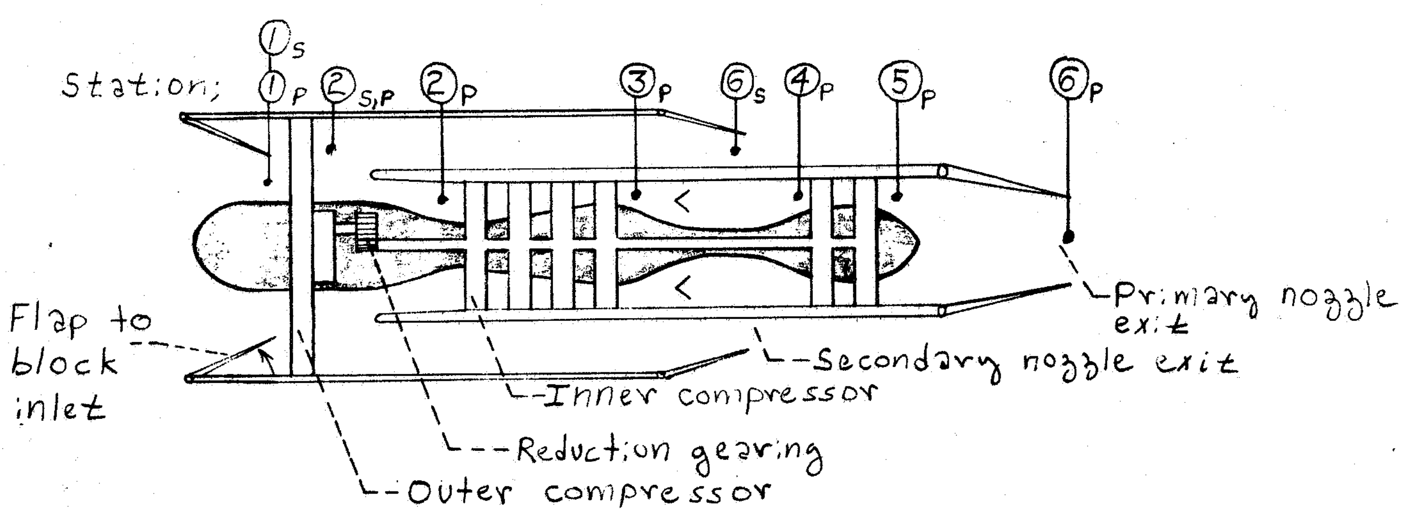


Figure 3.- Generalized turbine efficiency map.

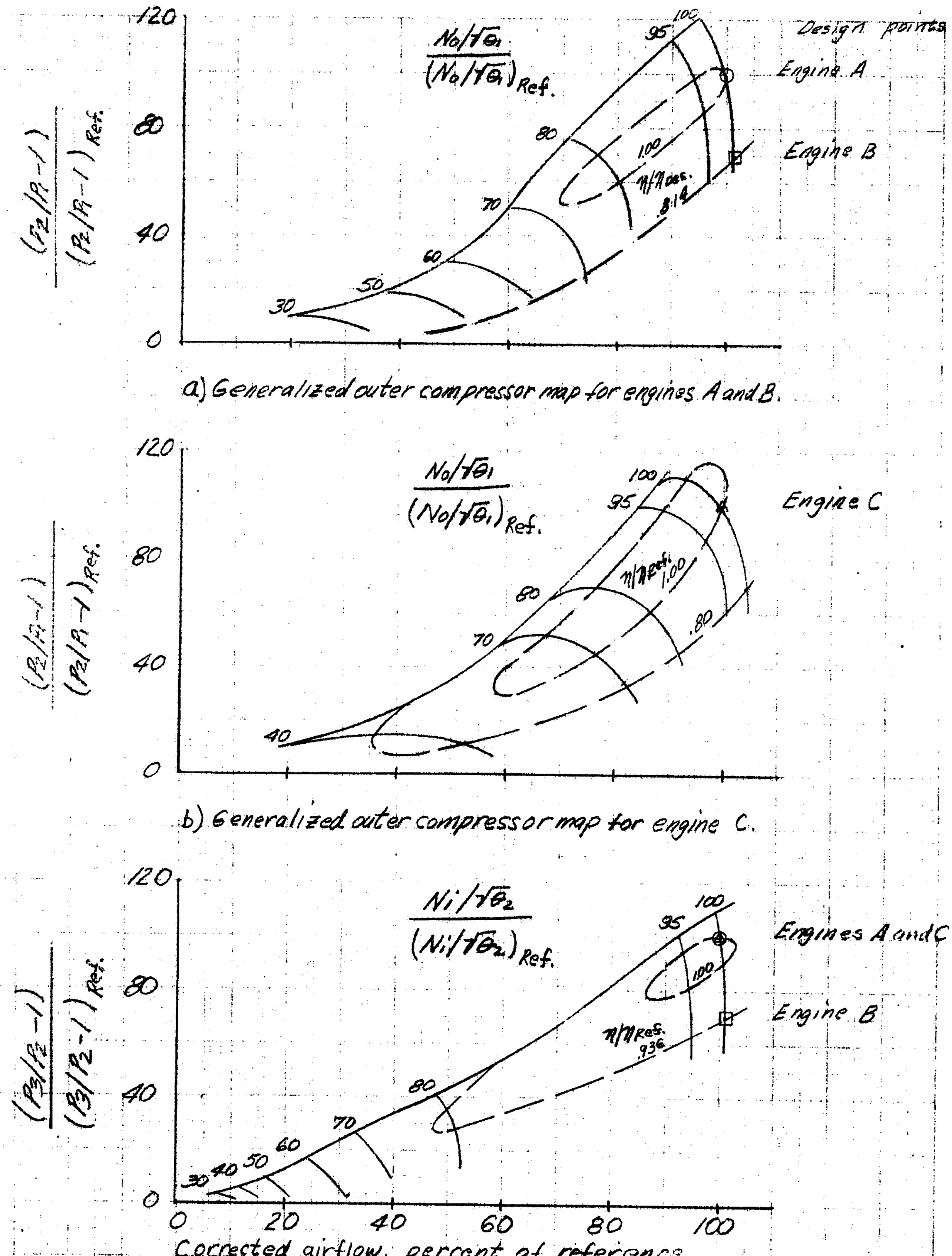


(a) Engines A and B. $(P_2/P_1)_p = 1.0$



(b) Engine C. $(P_2/P_1)_p > 1.0$

Figure 4. - Engine configurations investigated.

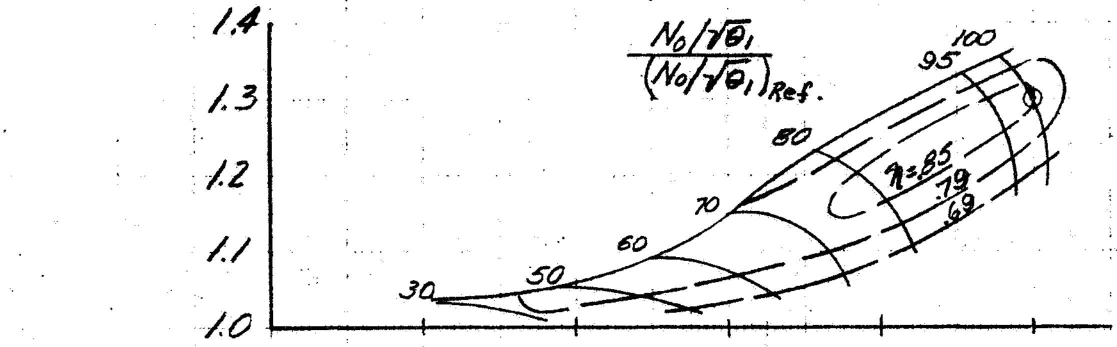


a) Generalized outer compressor map for engines A and B.

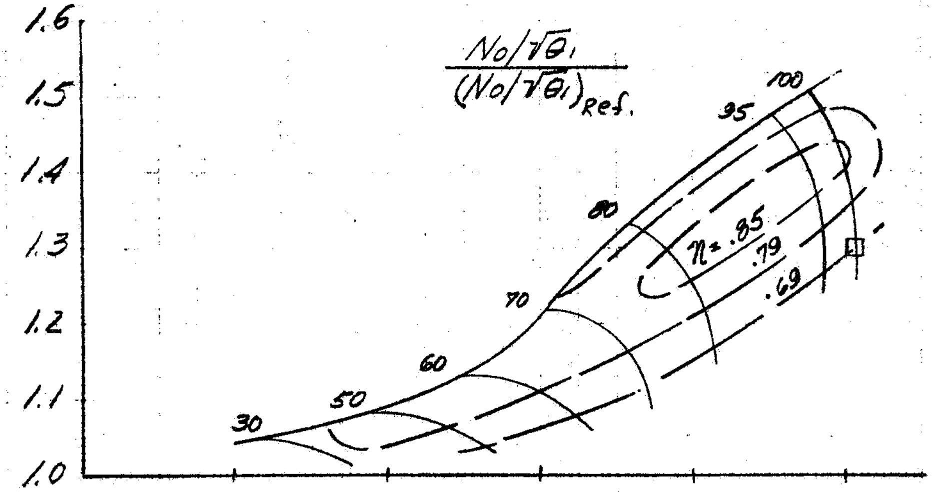
b) Generalized outer compressor map for engine C.

c) Generalized inner compressor map for engines A, B, and C.

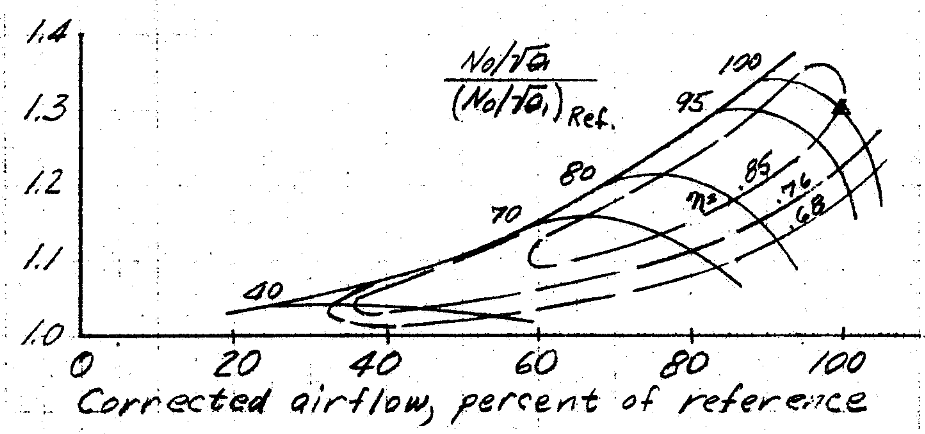
Figure 5.- Compressor maps for engines A, B, and C.



d.) Conventional outer compressor map for engine A.

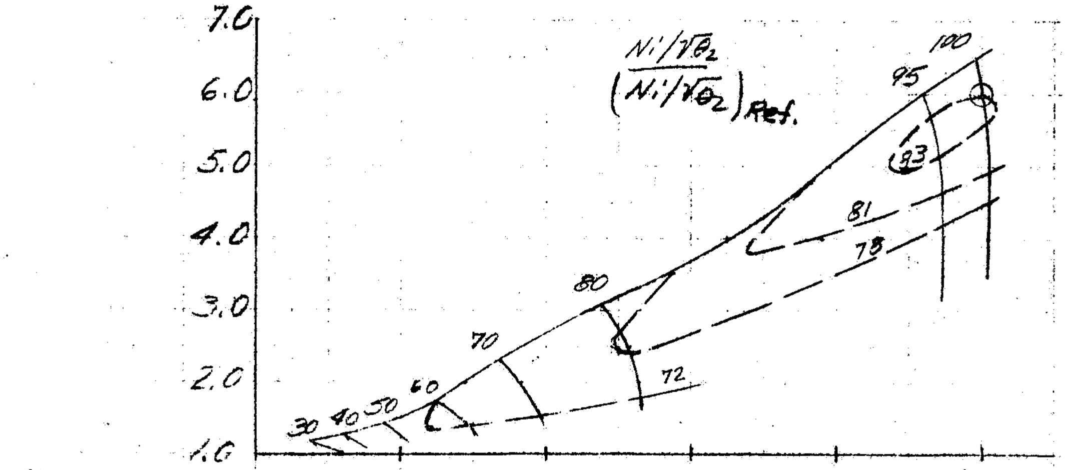


e.) Conventional outer compressor map for engine B.

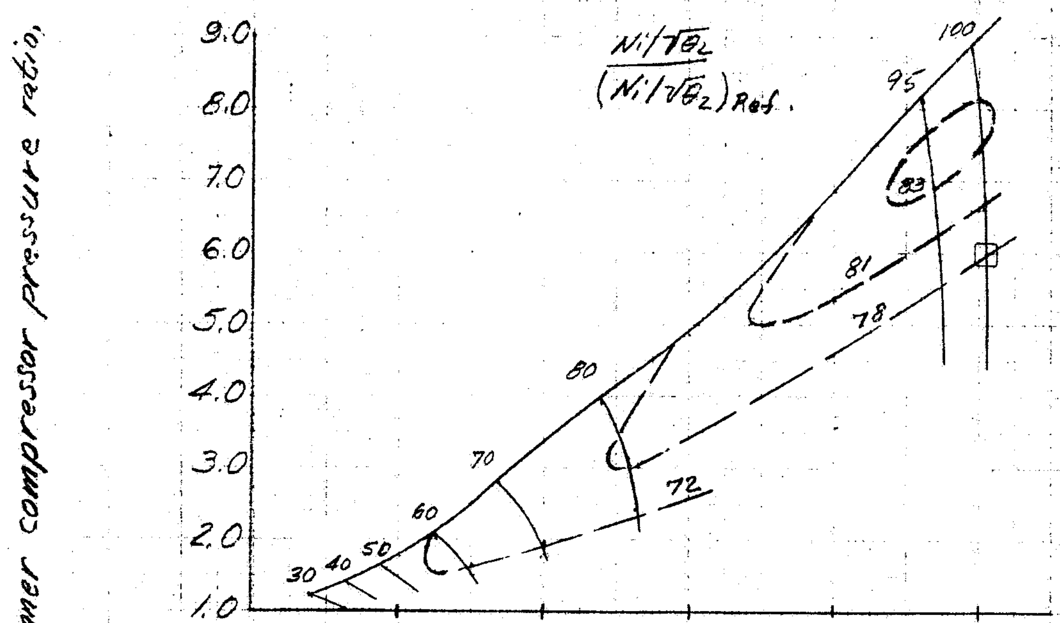


f.) Conventional outer compressor map for engine C.

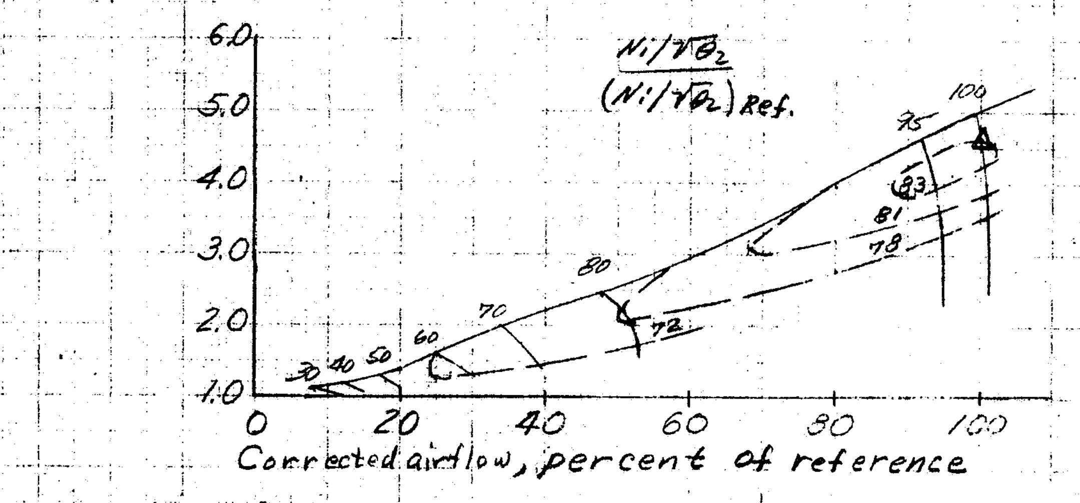
Figure 5.- Continued



g) Conventional inner compressor map for engine A.

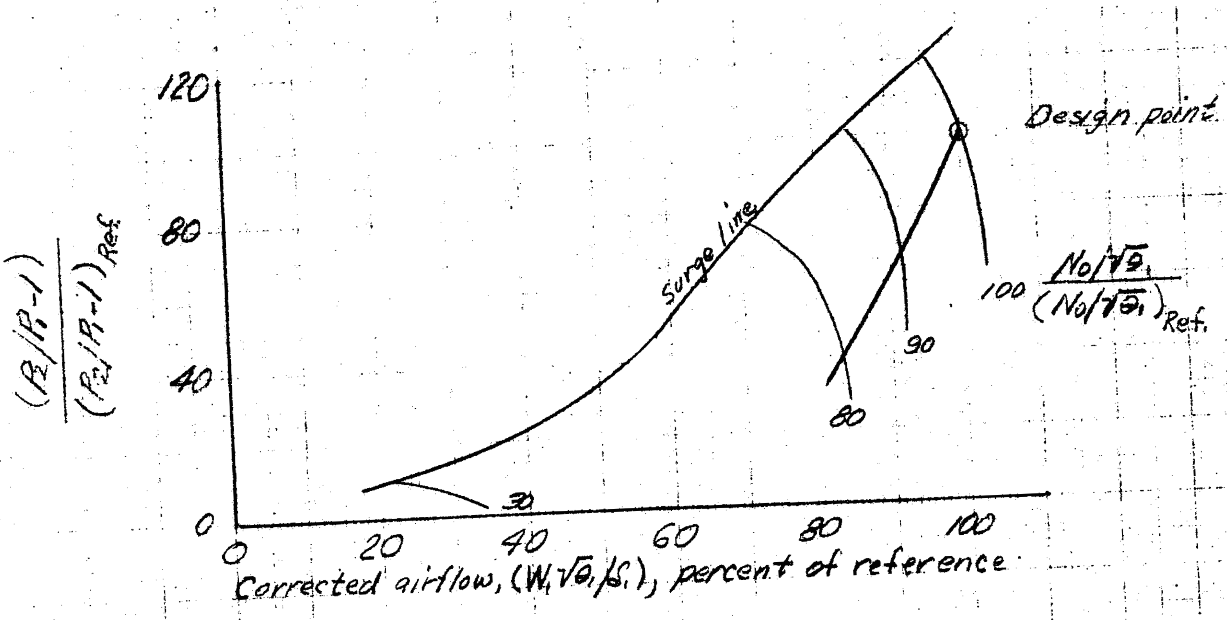


h) Conventional inner compressor map for engine B.

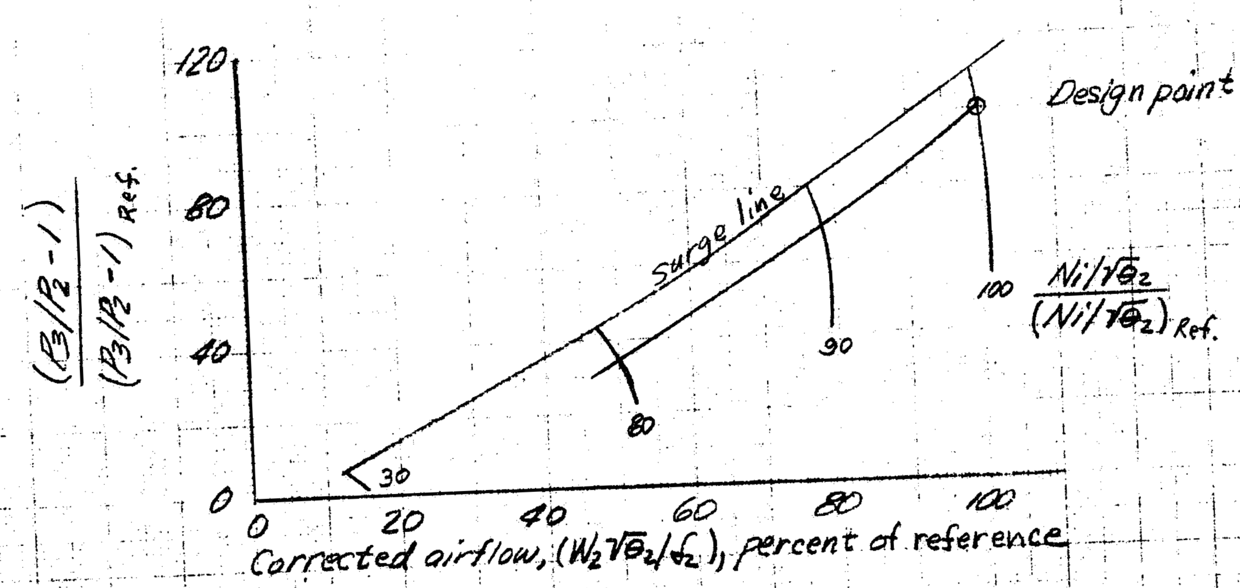


i) Conventional inner compressor map for engine C.

(Figure 5.- Concluded)

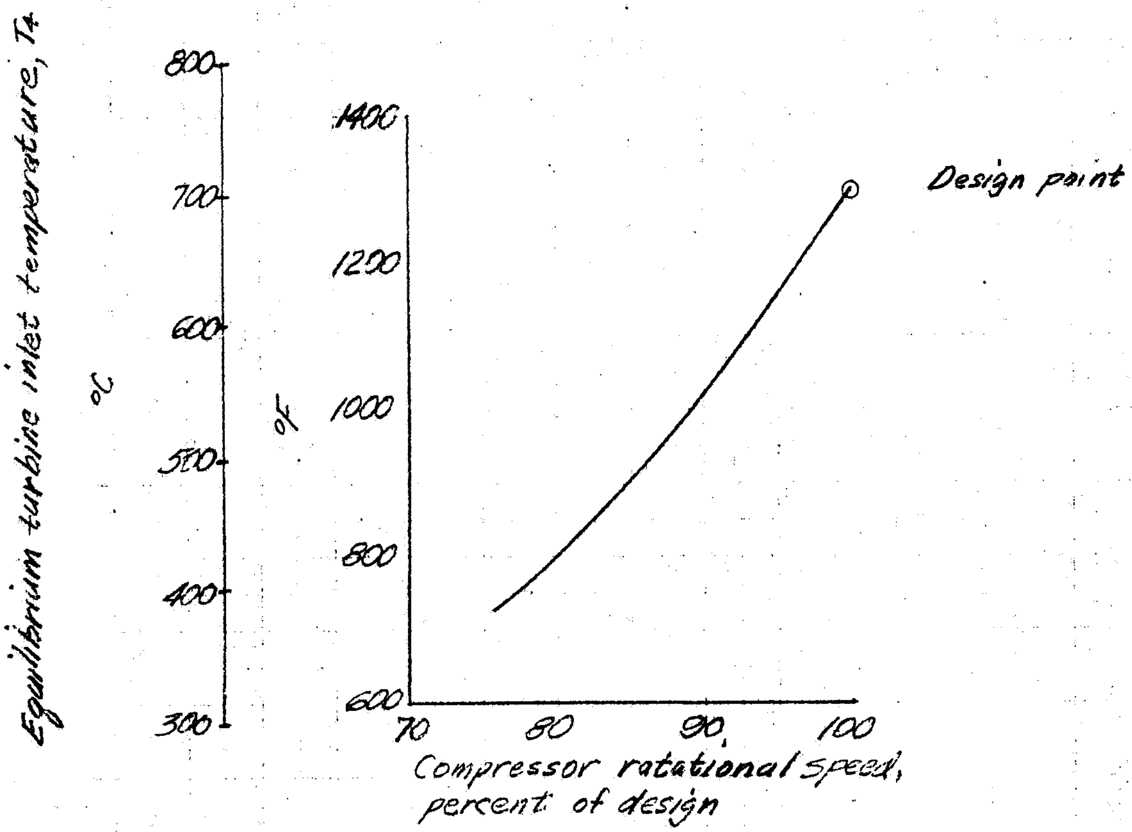


a) Outer compressor map

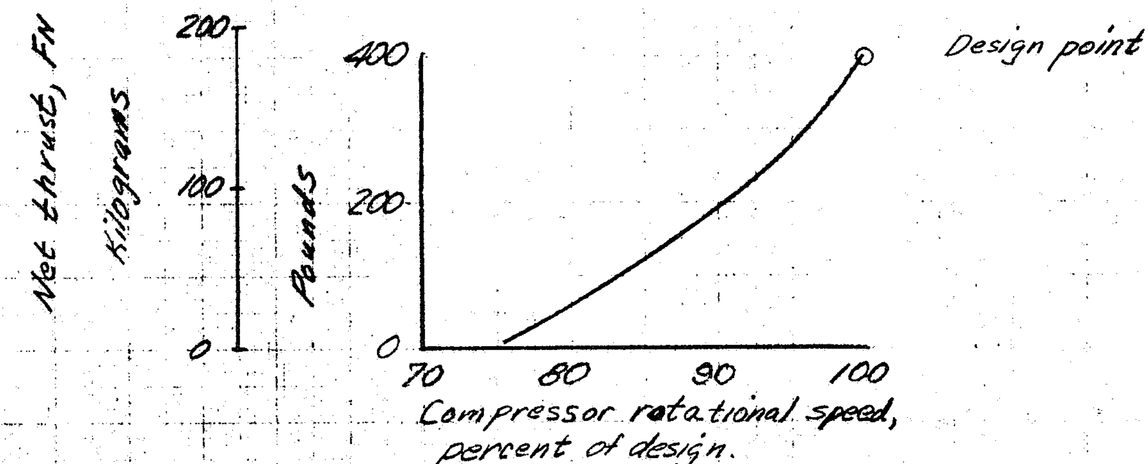


b) Inner compressor map

Figure 6.– Generalized compressor maps showing the operating lines at cruise for engine A. Nozzle exit areas are 100 percent of design.



a) Effect on equilibrium turbine inlet temperature



b) Effect on net thrust

Figure 7.- The effect of compressor rotational speed on engine equilibrium performance at cruise with design values of nozzle exhaust areas.

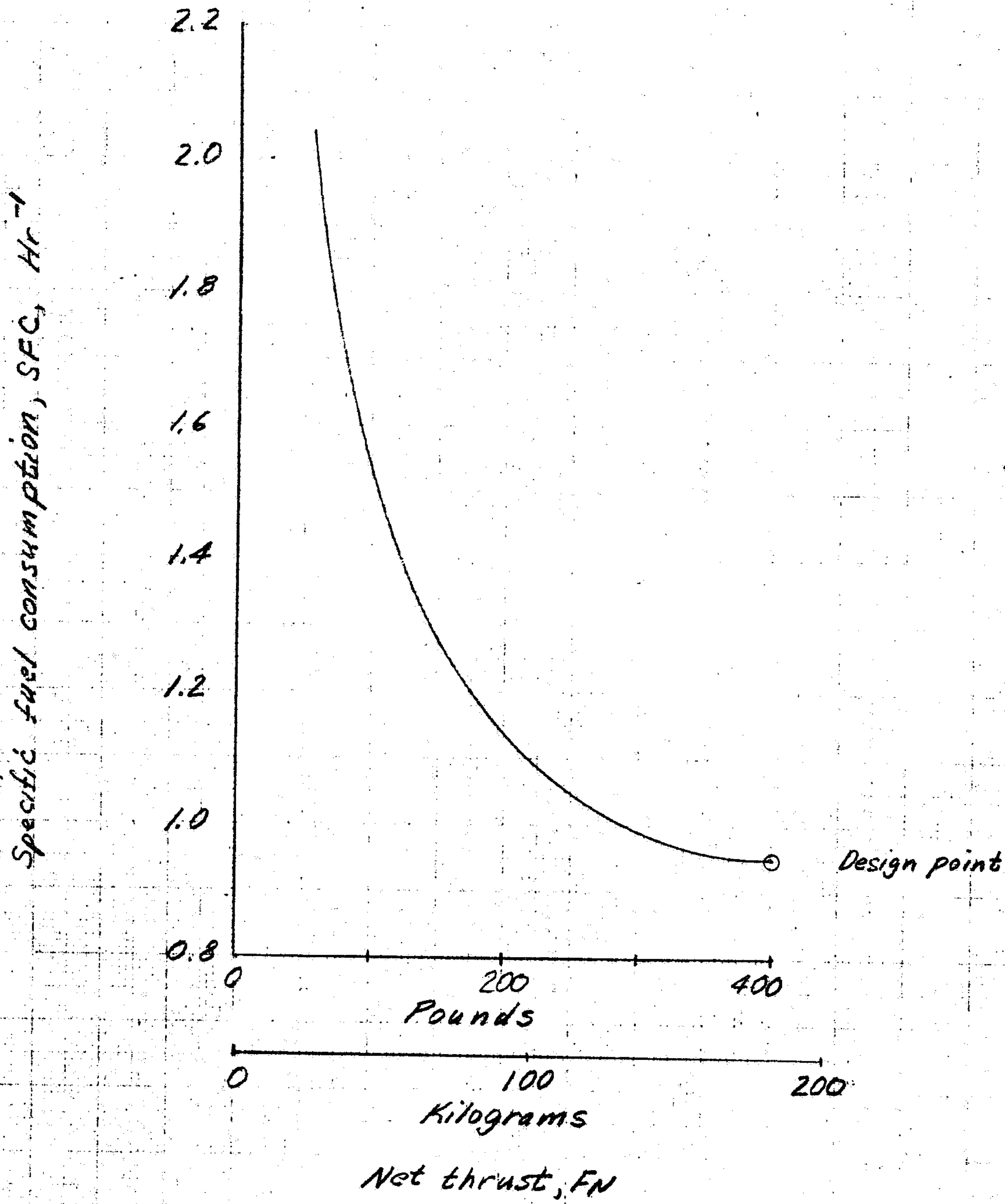
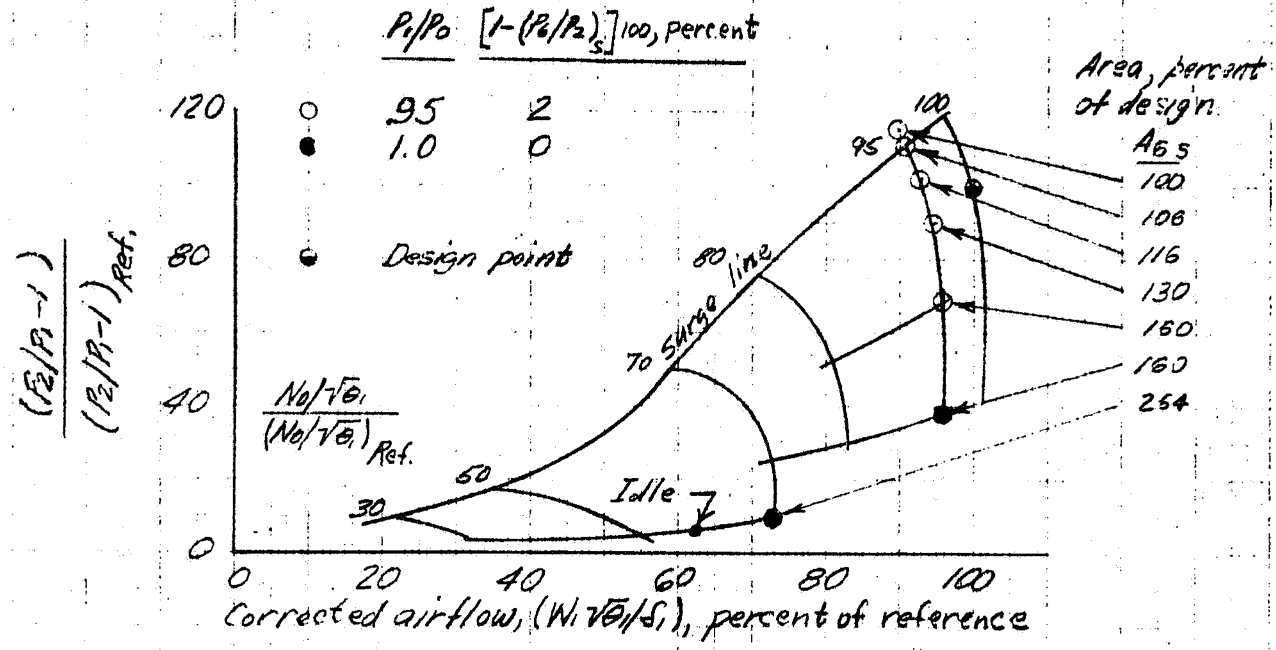
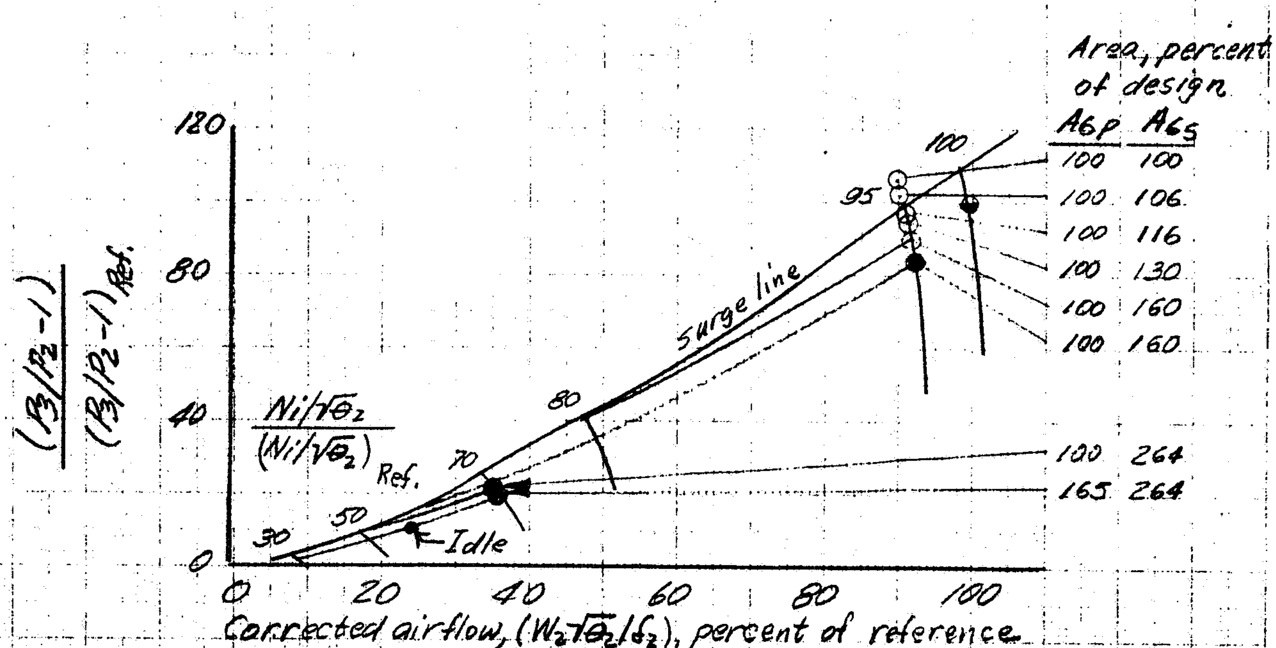


Figure 8.– The effect of engine net thrust on specific fuel consumption at cruise with design values of nozzle exhaust areas.



a) Outer compressor map



b) Inner compressor map

Figure 9.- Generalized compressor maps of engine A showing the effects of varying primary and secondary exhaust areas. Sea-level-static operation.

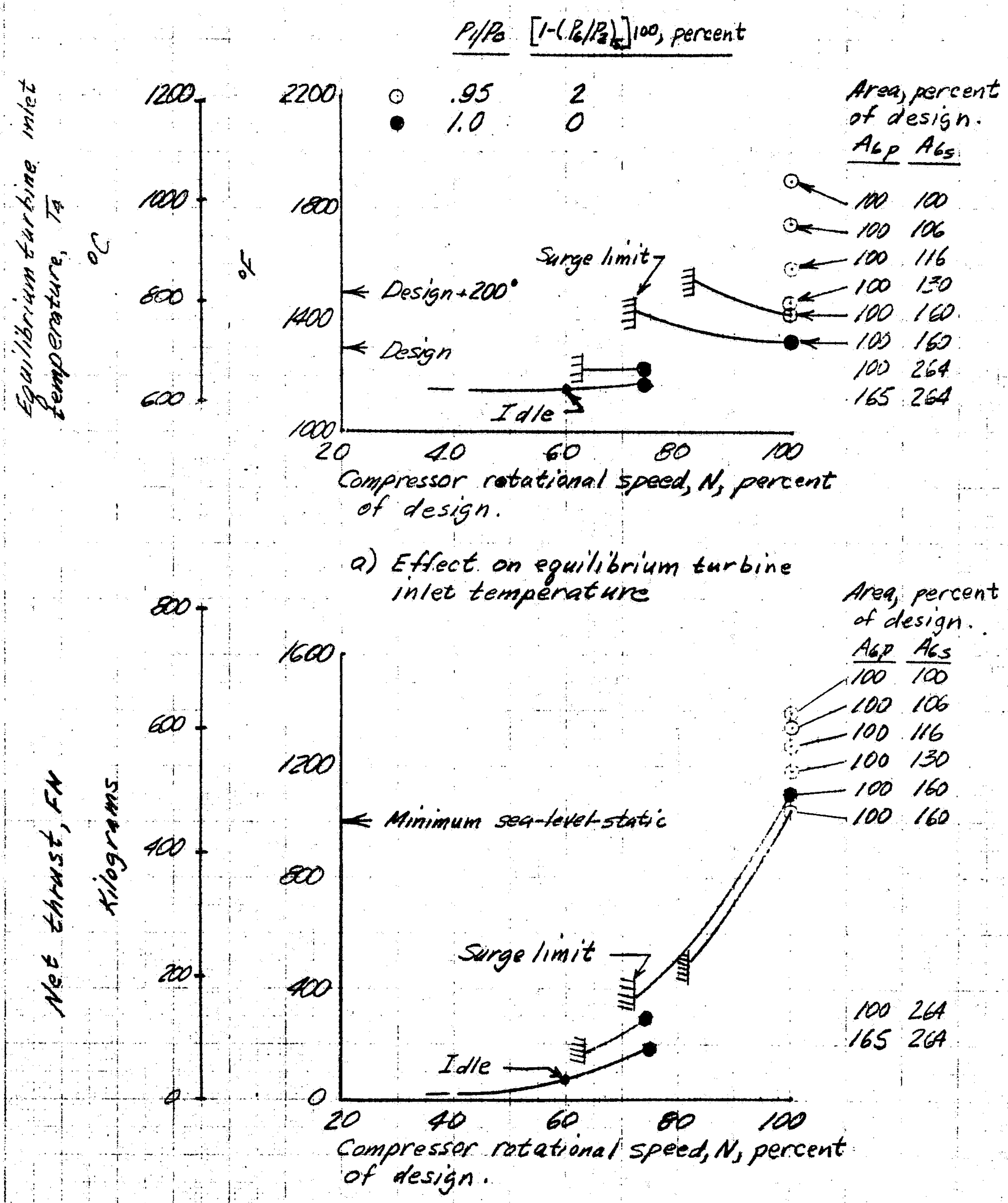
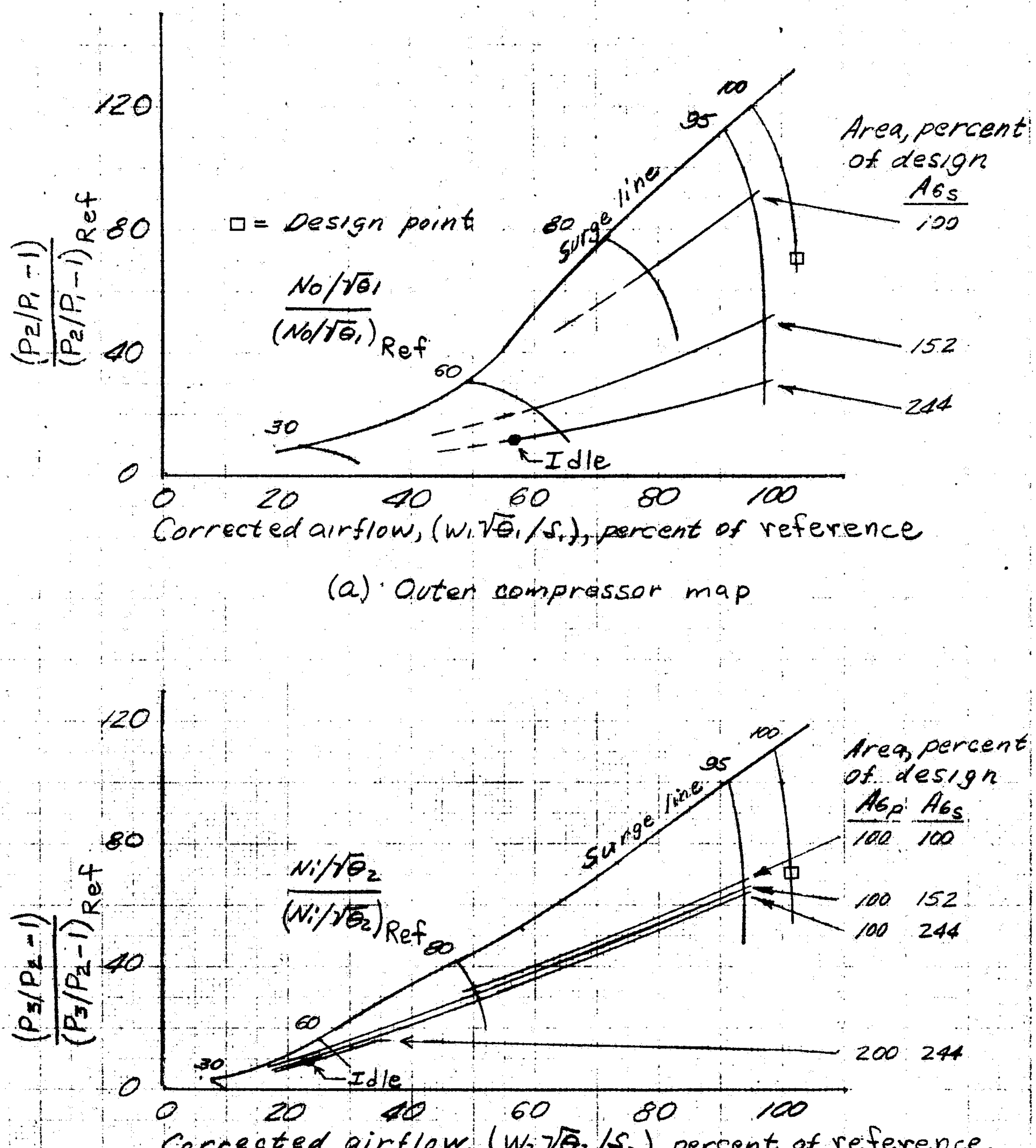


Figure 10.- The effect of compressor rotational speed on equilibrium performance of engine A at sea-level-static conditions with variable primary and secondary exhaust areas.



(a) Outer compressor map

(b) Inner compressor map

Figure 11 - Generalized compressor maps of engine B showing the effects of varying primary and secondary exhaust areas. Sea level static conditions.

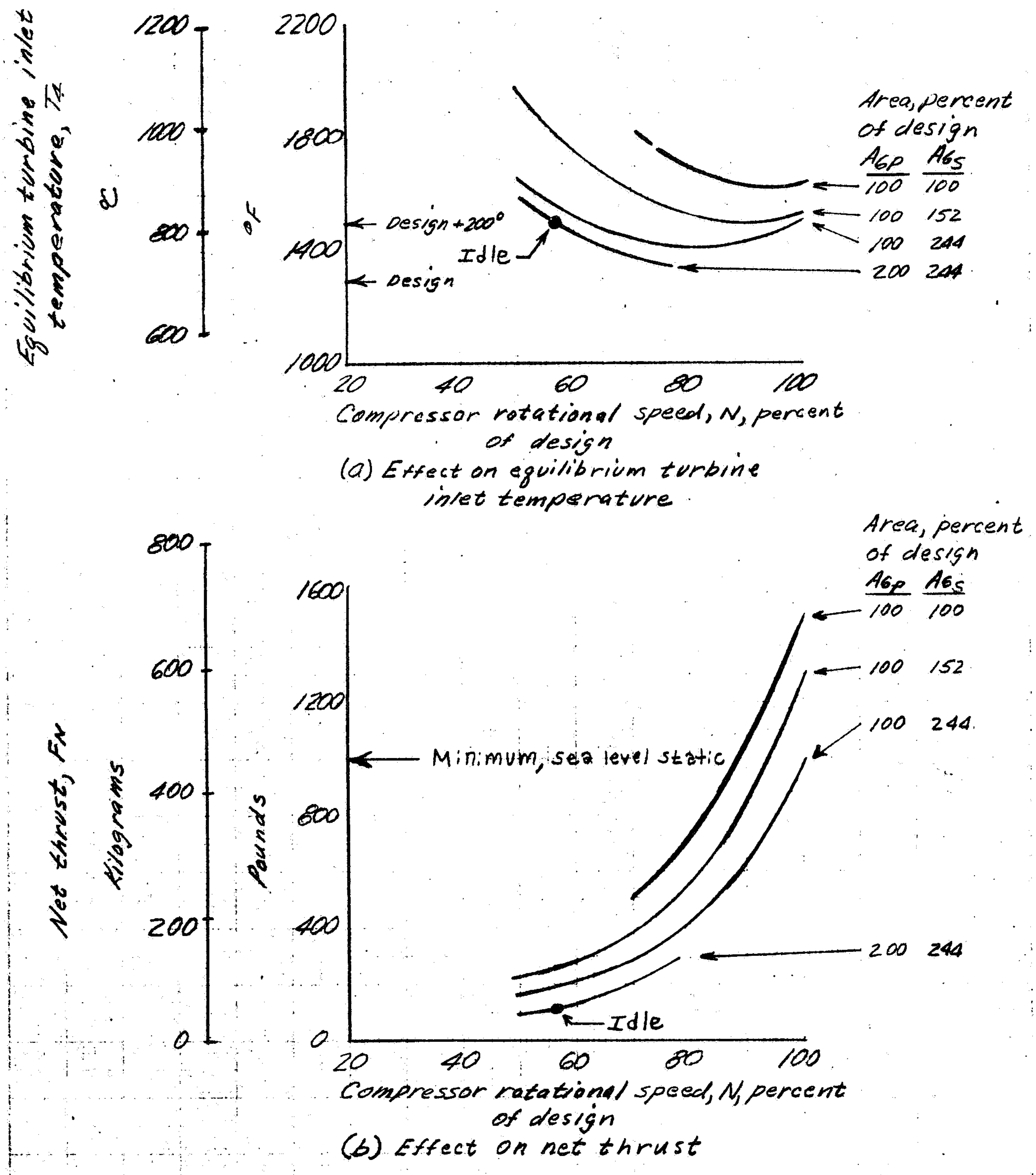
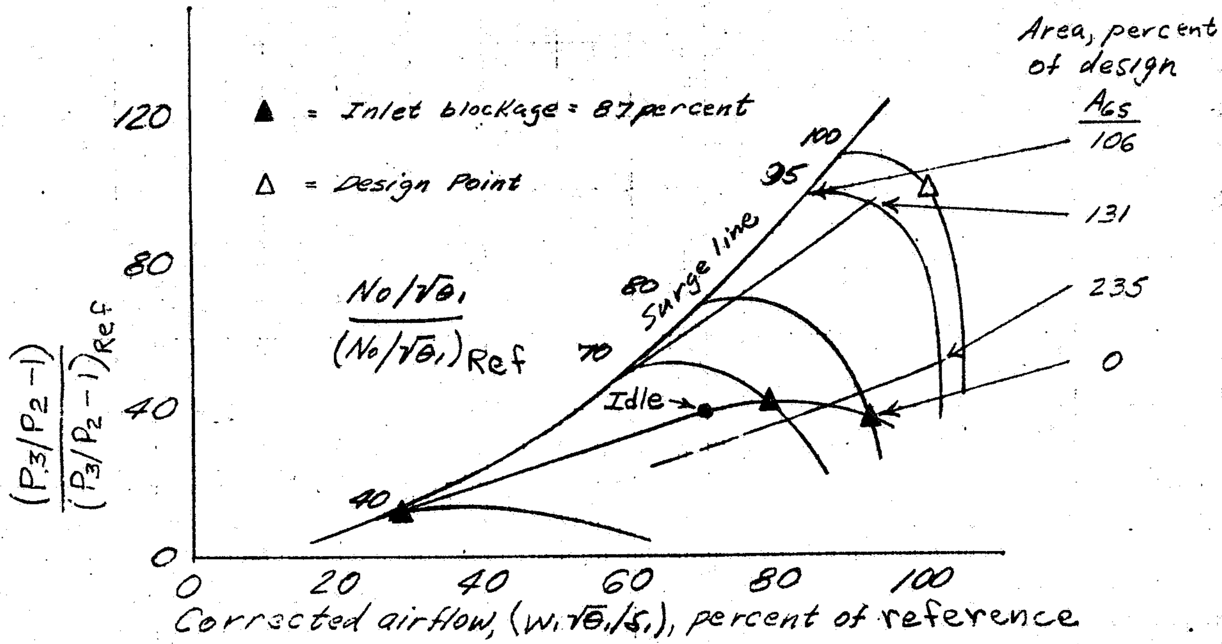
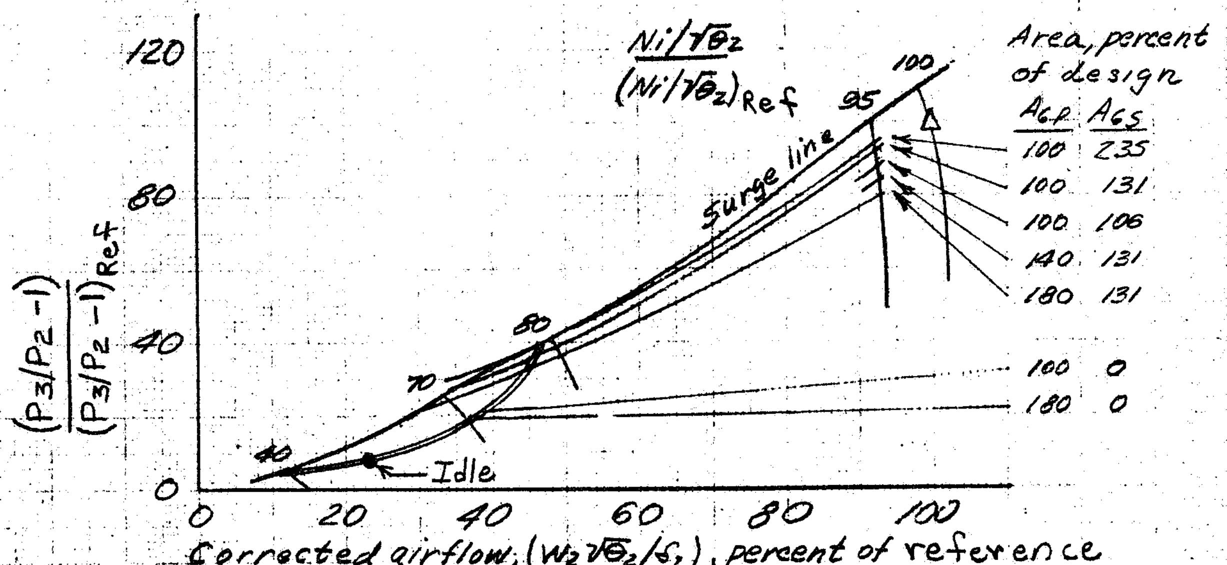


Figure 12 - The effect of compressor rotational speed on equilibrium performance of engine B at sea level static conditions with variable primary and secondary exhaust areas.



(a.) Outer compressor map



(b) Inner compressor map

Figure 13. - Compressor maps of engine C showing the effects of inlet blockage, and of varying primary and secondary exhaust areas. Sea level static operation.

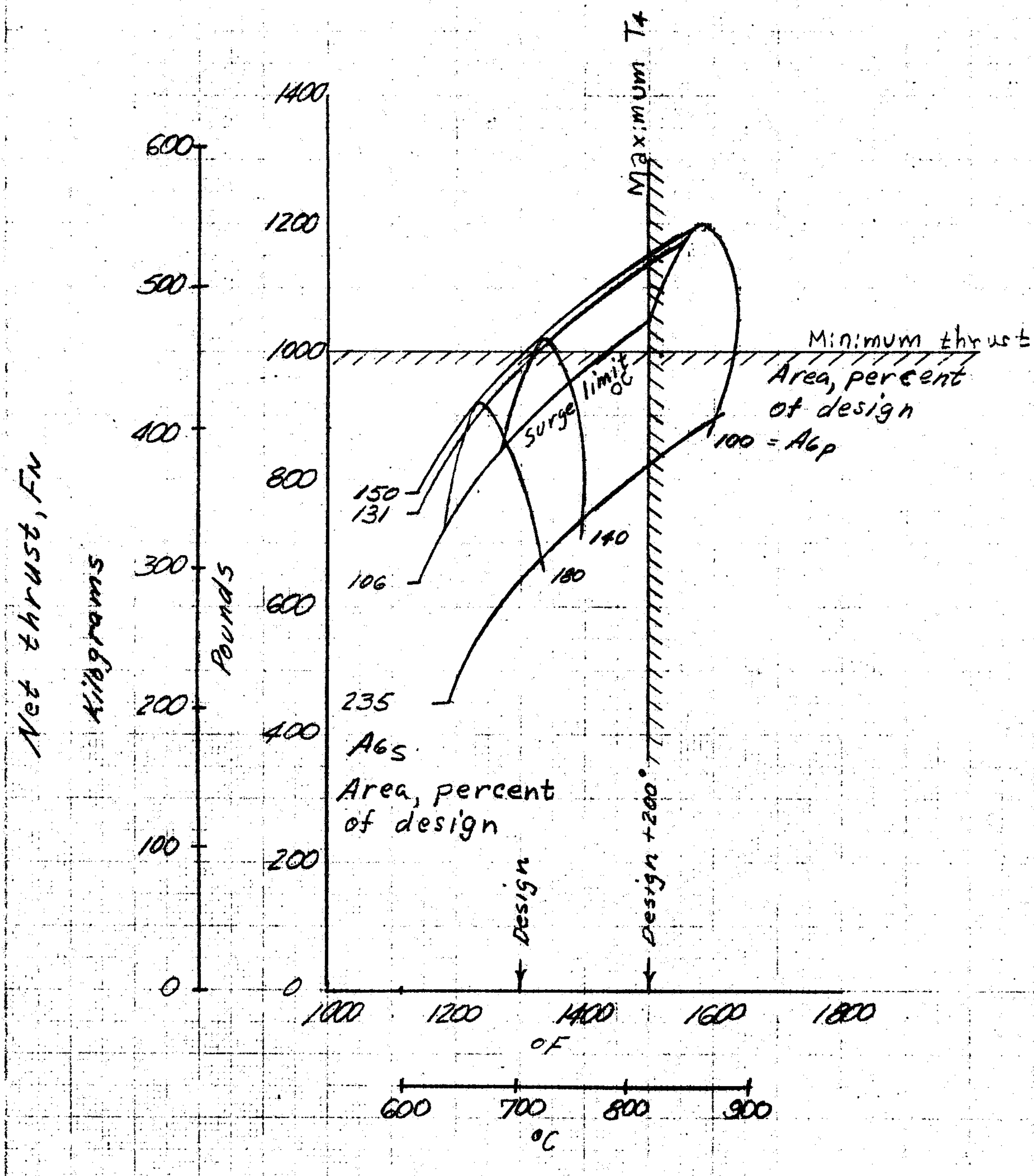


Figure 14.- A range of possible combinations of equilibrium turbine inlet temperature and net thrust at 100 percent of design compressor rotational speed for engine C. Sea level static conditions.

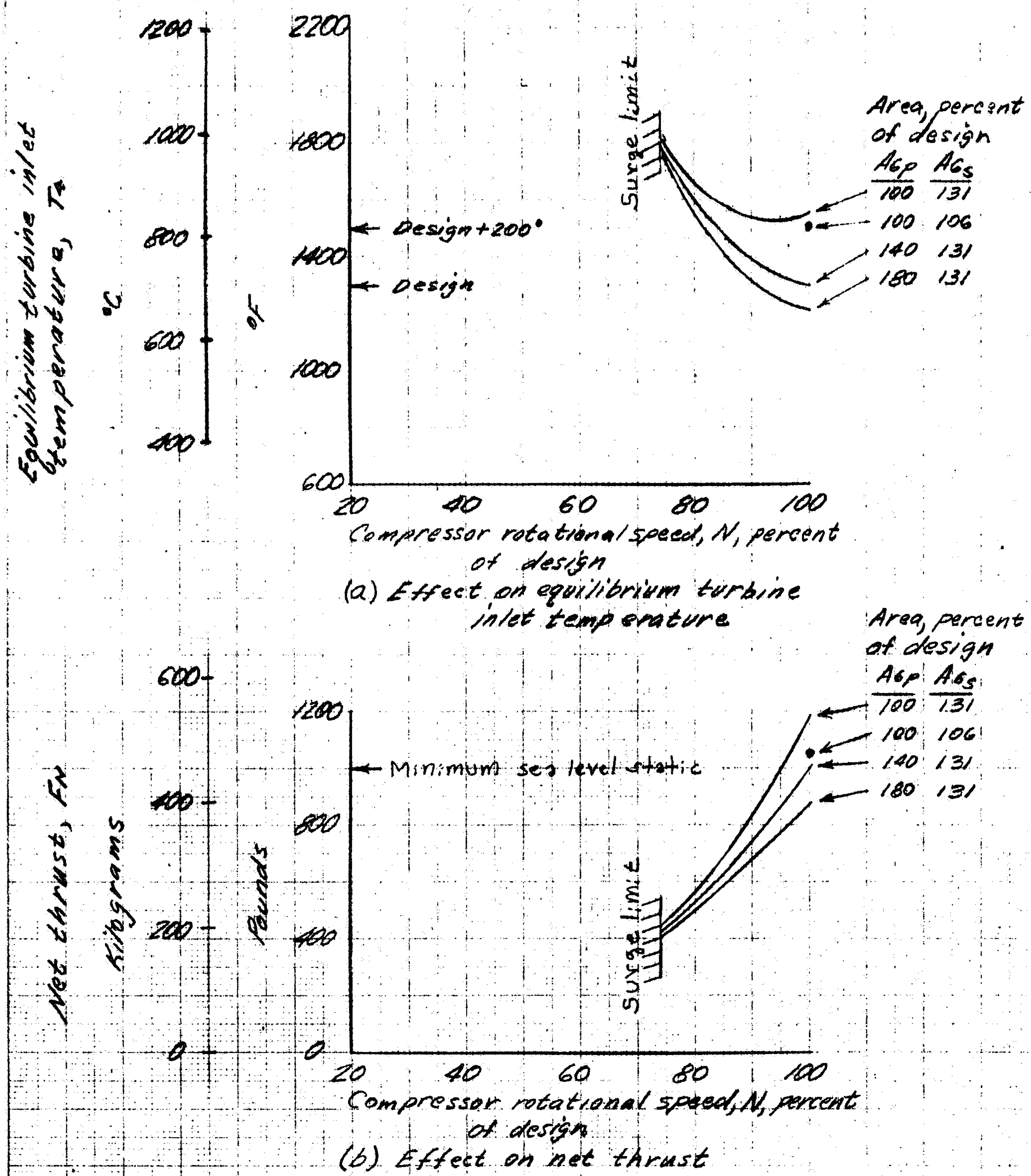


Figure 15.- The effect of compressor rotational speed on equilibrium performance of engine C at sea level static conditions with variable primary and secondary exhaust areas.

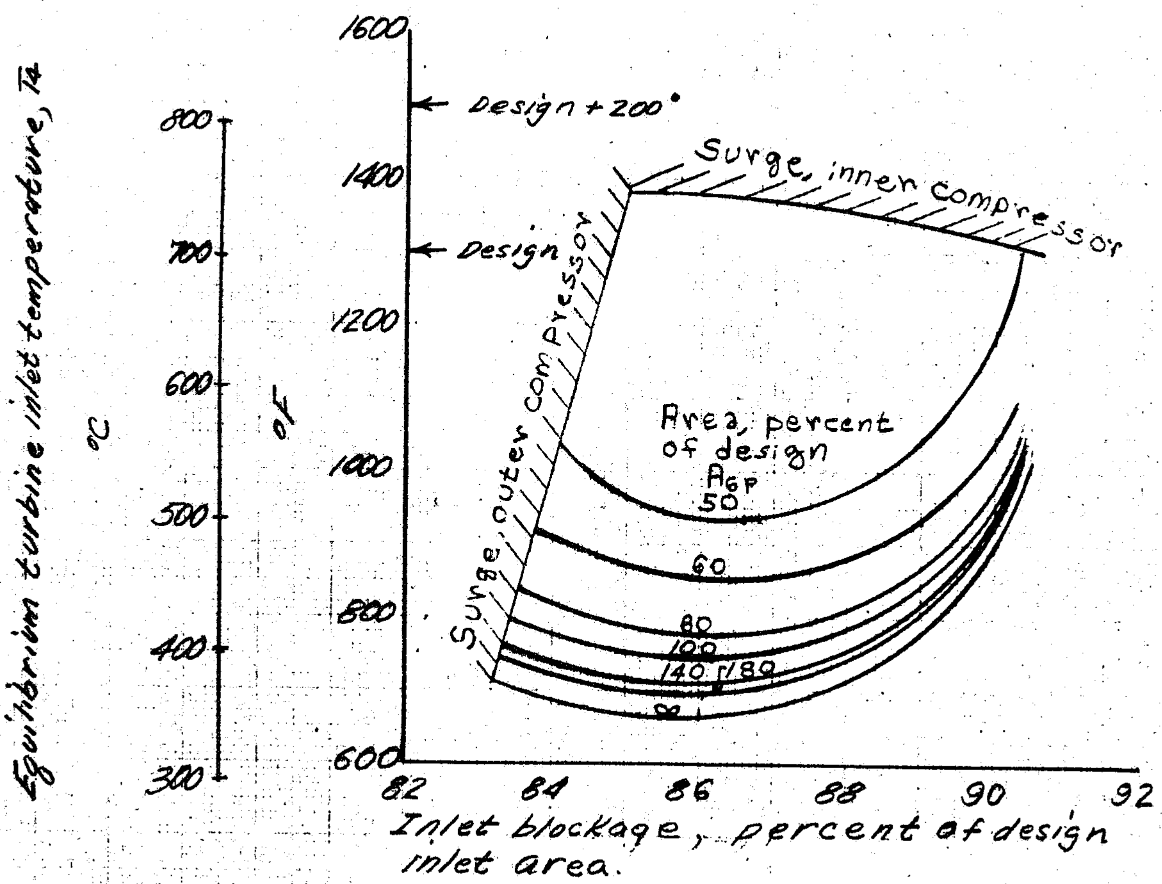


Figure 16.– A range of possible combinations of equilibrium turbine inlet temperature and inlet blockage at 74 percent of design compressor rotational speed for engine C. Sea level static conditions. Secondary exhaust area completely closed.

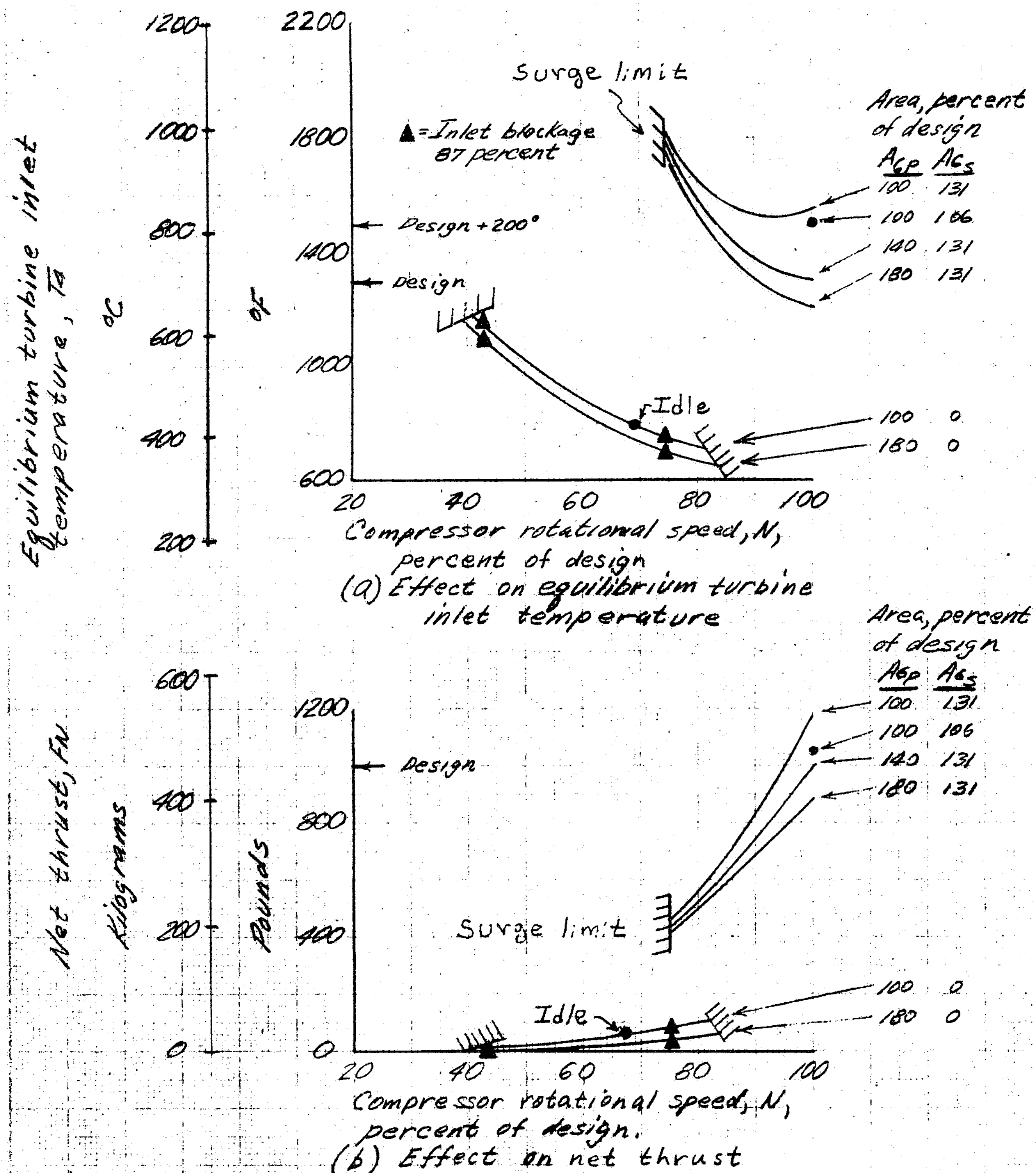


Figure 17.- The effect of compressor rotational speed on equilibrium performance of engine C at sea level static conditions. Variable primary and secondary exhaust areas as well as a fixed inlet blockage are used.